VALIDATION OF SURFACE PERFORMANCE-GRADED SPECIFICATION FOR SURFACE TREATMENT BINDERS

A Thesis

by

AISHWARYA VIJAYKUMAR

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

August 2012

Major Subject: Civil Engineering

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Approved by:

Chair of Committee,	Amy Epps Martin
Committee Members,	Robert L Lytton
	Charles J Glover
Head of Department,	John Niedzwecki

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ABSTRACT

Validation of Surface Performance-Graded Specification For Surface Treatment Binders.

(August 2012)

Aishwarya Vijaykumar, B.Tech., Jawaharlal Nehru Technological University

Chair of Advisory Committee: Dr. Amy Epps Martin

The design and selection of surface treatment binders in service is currently based on specifications that only account for the penetration and ductility of emulsion residues or the penetration and viscosity of hot-applied asphalt cements. These specifications consider neither the entire range of temperatures that the binders may be subjected to during production and in service, nor long-term aging behavior. A surface performance-graded (SPG) specification for the selection of surface treatment binders was developed as part of previous Texas Department of Transportation (TxDOT) and National Cooperative Highway Research Program (NCHRP) projects. The work performed under the TxDOT Project 0-6616 was the basis for this thesis. In this project, the SPG specification, which is performance-based and takes into account the physical properties of the binder at the temperature ranges in which the material will be used, was further validated. This was accomplished by standardizing the emulsion residue recovery method through the evaluation of two warm oven methods, exploring the exclusive use of the dynamic shear rheometer (DSR) for determining performance-based properties,

and further field validating the thresholds for these properties. The laboratory and field results were used to revise the SPG specification for surface treatment binders in service.

Binder samples collected from chip seal projects constructed on selected highway sections in Texas in summer 2011 were tested and graded according to the existing SPG specification developed in previous research projects. Two warm oven emulsion residue recovery methods were used and compared. New DSR tests, including the multiple stress creep recovery (MSCR) test and the frequency sweep test were evaluated for developing additional criteria in the SPG specification. The SPG grades of the surface binder samples evaluated from laboratory tests were compared with the actual field performance of the highway sections one year after construction. The SPG specification was found to be functional in terms of enabling the selection of binders to ensure adequate surface treatment performance. Moreover, the results obtained from the MSCR and DSR frequency sweep tests were compared with field performance to develop additional criteria in the specification. Further validation is recommended to investigate the effects of construction and quality control processes, as this study is limited to producing a revised SPG specification for properties that address stiffness and aggregate retention in service.

DEDICATION

To my parents, my permanent source of inspiration

To Ashok Gorrepati, for all the reasons he knows so well

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TABLE OF CONTENTS

LIST OF FIGURES

Page

LIST OF TABLES

Page

CHAPTER I

INTRODUCTION

Surface treatments are an essential part of pavement preservation programs adopted by the Texas Department of Transportation (TxDOT) and other highway agencies aiming to maintain and improve the condition of asphalt pavements. This thesis study validates a performance-based grading system for surface treatment asphalt binders in use in Texas. The study explores the recovery, testing, and characterization of emulsion residues and hot-applied asphalt cements used in surface treatments in order to develop a surface performance-graded (SPG) specification. The research conducted for this thesis was performed as part of the Texas Department of Transportation (TxDOT) Project 0-6616: Validate SPG Specification for Surface Treatment Binders. The following sections will provide an overview of the performance grading of surface treatment asphalt binders, the development of the SPG system, and the research tasks undertaken as part of this study.

Background

Surface treatments are defined in TxDOT specifications (Item 316) as an application of asphaltic material covered with aggregate (TxDOT 2004). The specification allows for single, double, or triple spray applications of hot-applied asphalt

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This thesis follows the style of the *ASCE Journal of Materials in Civil Engineering.*

cements, asphalt emulsions, or cutback asphalts, each covered with aggregate. The application of surface treatments is a simple, inexpensive, and effective preventive maintenance strategy to obtain a durable, weatherproof hot-mix asphalt (HMA) surface.

The performance of surface treatments depends on the careful construction as well as the properties of the asphalt binder and the aggregates used. Epps et al. (1981) have recommended that surface treatment binders should (a) be fluid enough to be sprayed yet viscous enough to be applied uniformly; (b) have sufficient consistency to wet and adhere to aggregate quickly; (c) be able to retain the aggregate upon curing; and (d) be resistant to excessive deformation under varying traffic loads as well as weather conditions.

Currently, the design and selection of surface treatment binders is based on specifications that only account for the penetration and ductility of emulsion residues or the penetration and viscosity of hot-applied asphalt cements. Current specifications for the binding materials used in surface treatments (Item 300) consider both the properties of the material during construction and in service, and a wide range of materials can be utilized to meet the current specified properties (TxDOT 2004). These specifications consider neither the entire range of temperatures that the binders may be subjected to during production and in service nor behavior after long-term aging. A surface performance-graded (SPG) specification for the selection of surface treatment binders was developed as part of TxDOT Project 1710 and NCHRP Project 14-17 (Shuler et al. 2011; Walubita and Epps Martin 2005b). The SPG system relates the properties of surface treatment asphalt binders to the conditions under which they are used; it accounts for the effects of the expected climatic conditions, pavement temperatures, and aging on the performance of the binder.

Problem Statement

Advances in binder testing during the Strategic Highway Research Program (SHRP) led to the implementation of a performance-graded (PG) specification and associated grade selection process for binders used in HMA (AI 2003; McGennis et al. 1994). In this specification system, binders are tested in three critical aging states using laboratory tests that measure physical properties directly related to the performance of HMA mixtures. The development of these tests addressed many shortcomings of the previous viscosity- or penetration-graded specification systems, including the empirical nature of penetration and ductility tests, the limited temperature range for determination of physical properties, and the lack of consideration for long-term aging. The Superpave PG specification for HMA employs many new tests that require the physical properties of the binder to be specified at the temperature ranges in which the material will be used. These properties are specified to preclude the three primary forms of distress in HMA: rutting, fatigue cracking, and thermal cracking. The temperature range where the specified properties are met is defined as the binder grade, and this range spans from the very high temperatures the binder is exposed to during production and construction to the large range from high to low temperatures the binder is subjected to in service. Both short- and long-term aging are considered in the PG system through the use of the rolling thin film oven test (RTFOT) and the pressure-aging vessel (PAV), respectively (2003; McGennis et al. 1994). The associated binder grade selection process uses environmental data for a specific highway section (HS)to select the grade required for use in HMA that will provide adequate performance at a selected reliability level (2003; McGennis et al. 1994). Further, it was recommended that traffic data be used to increase the high temperature grade, if necessary, to account for either slow-moving traffic or the anticipation of a large volume of traffic.

Using the PG system, performance is included in the binder specification and environmental and traffic conditions representative of those encountered by binders in HMA are addressed to ensure that the most appropriate binder is selected for its intended use. A similar specification system for binders used in surface treatments does not exist. The current specification for these materials in service relies on viscosity and penetration measurements and does not completely account for aging. The current specification must be updated to address the shortcomings of empirical tests, the determination of physical properties over a limited temperature range, which does not account for appropriate environmental conditions in service, and the lack of complete consideration for aging during construction and in service. Physical properties directly related to the performance of surface treatments must also be included in an improved specification. These include properties such as viscosity, strain tolerance, creep compliance and stiffness, low-temperature performance, and aging susceptibility, which influence sprayability, aggregate loss, bleeding, and cracking (Miller et al. 2010). It is recommended that surface binders be fluid enough to allow uniform application at the temperature of spraying, to enable quick bonding with aggregate and the underlying substrate, and to resist turning brittle and fracturing under loads at cold temperatures;

viscous enough to prevent aggregate loss under traffic load, and to prevent distortion under hot weather; and resistant to the effects of sunlight, air, and moisture damage (Epps et al. 1981).

Unfortunately, the PG system for HMA developed during SHRP and now implemented in Item 300 of the TxDOT specifications is not directly applicable to surface treatment binders due to differences in distress types, environmental conditions during production and in service, and construction methods and their effect on the performance of the binders. Through TxDOT Project 0-1710 and, more recently, in NCHRP Project 14-17, an SPG binder specification for surface treatment binders in service was developed and validated with field performance monitoring. Based on field validation, given proper construction and design, the estimated SPG grades and the field performance of surface treatment binders are well correlated (Walubita et al. 2004). The SPG system is an extension of the concept behind the SHRP PG classification system and utilizes the same laboratory testing equipment. However, as the criteria specified in the SPG system are primarily aimed at preventing aggregate loss and bleeding; the tests, thresholds, and parameters are different from those in the PG specification. This study aims to further revise and improve the SPG specification by adding additional performance parameters and revising and developing thresholds based on field performance under various climatic and traffic conditions.

Research Objective

This study pursues the following objectives to revise and validate the SPG specification:

- Evaluate methods for the recovery of emulsion residue from emulsified asphalt binders used in surface treatments
- Develop a testing protocol that enables exclusive use of the dynamic shear rheometer (DSR)
- Test, characterize, and grade emulsion residue and hot-applied asphalt cements for performance in surface treatments
- Recommend a revised performance-based specification for asphalt binders used in surface treatments

Recommendations based on this study will be made to TxDOT toward the implementation of the SPG system for selecting asphalt binders for surface treatments..

Thesis Outline

This thesis is organized into five chapters. Chapter I provides background information on the need for the SPG specification, the research objectives, and thesis contents. Chapter II is a literature review that examines previously developed SPG systems and summarizes the major research findings related to the characterization of asphalt binders used in surface treatments. The available test methods used to evaluate the susceptibility of surface binders to the most common distresses—aggregate loss and bleeding—are explored. Chapter III describes the experimental design, including the methodology and materials used. The results of laboratory evaluation and field monitoring are presented and analyzed in Chapter IV. Lastly, Chapter V summarizes the conclusions and recommendations developed based on completion of all the tasks in this study.

CHAPTER II

LITERATURE REVIEW

This section presents a comprehensive review of information on the various methods for characterizing the properties of surface treatment binders, including relevant national and international research on emulsion residue recovery, the development of the SPG specification, exclusive use of the DSR for rheological testing of binders, binder-aggregate compatibility in terms of adhesion, and aging.

Emulsion Residue Recovery Methods

The laboratory tests for characterizing the performance of surface treatment asphalt binders are typically performed using the binder residue and not the emulsion itself. In order to characterize the material accurately, it is important that the residue obtained in the laboratory is representative of the emulsion residue used in the field. The ideal emulsion residue recovery method should yield a sufficient amount of residue for testing, eliminate the most moisture, be suitable for recovery of residue at lower temperatures to preserve the microscopic structure of the binder, and not be excessively time consuming. A recent Federal Lands Highway draft specification for polymer-modified emulsions discusses various methods for the recovery of emulsion residues (King et al. 2010). This study reiterates the finding that methods involving recovery at high temperatures result in changes in the morphology of the emulsion and do not allow for accurate prediction of the in-service performance of the binders (Takamura 2000).

Further, the extremely high temperatures utilized in some methods are not representative of the temperatures experienced at any stage in the life cycle of emulsion residues in the field.

(Kucharek 2010) compared several distillation methods, including classical distillation, vacuum distillation, moisture balance analyzer, and Karl Fischer titration, with newly developed evaporative techniques. The study revealed that recovery through evaporation ages emulsion residues more than distillation, especially in the case of unmodified emulsion; further, evaporation was found to produce residues with higher complex shear moduli values. Moreover, compared to evaporation, distillation produces residue with properties closer to those of the base binder used to produce the emulsion. In a 2008 study, existing evaporative and distillation techniques for residue recovery were compared with the new moisture analyzer balance (MAB) procedure (Salomon et al. 2008). At only 20 minutes, the MAB procedure is faster than the other techniques, in addition to being automated and more accurate. It has also been found to recover the same amount of binder as evaporation. However, preliminary rheological testing on the residue recovered using each method revealed that, except in the case of modified cationic rapid-setting type emulsions, the MAB procedure causes more aging than evaporation or distillation. The researchers attributed this to the high surface area of the samples in MAB relative to their volume, which may cause more oxidation. Therefore, it has been suggested that recovery using the MAB be performed at a lower temperature or in the absence of air.

Walubita et al. (2005a) studied five methods of emulsion residue recovery: hot oven, rotavap, hot plate, stirred can, and distillation. Based on the extent of moisture removed, the extent of asphalt oxidation observed by means of Fourier transform infrared spectroscopy (FTIR), and the quantity of residue obtained, the research team concluded that the stirred can method is best suited for emulsion residue recovery.

A recently standardized low-temperature emulsion recovery method called the force draft oven method is believed to reflect the temperature conditions during the setting of emulsions more closely. The hot-oven and stirred can methods were compared with the force draft oven method, in order to investigate the effect of each recovery method on the chemical and physical properties of binders (Mitchell et al. 2010). The force draft oven method was found (using size exclusion chromatography) to produce residue with a small detectable amount of moisture. Further, the force draft oven method produced residue that was statistically different from the residue obtained from the other two methods in terms of carbonyl area and low shear rate viscosity. Another study revealed that the force draft oven method does not lead to the degradation of the binder morphology during recovery (Gueit et al. 2007). The emulsion residue and the base asphalts showed different performance in elastic recovery and penetration tests, suggesting the possibility of aging during residue recovery or emulsification (Gueit et al. 2007; Hoyt et al. 2010).

Researchers are increasingly adopting the force draft oven method, owing to the ease with which the emulsion residue can be removed from molds, the close agreement of laboratory and field conditions, and acceptable reliability. The proposed standard for low-temperature evaporative residue recovery specifies two methods (ASTM 2009)—the force draft oven method (ASTM D7497-09 Method A) and the Texas oven method (ASTM D7497-09 Method B). The Texas oven method enables faster recovery (6 h) of emulsion residue than the force draft oven method (48 h) (Kadrmas 2010). Recent research indicates that 48 h of curing is essential in the forced draft oven method (ASTM D7497-09 Method A) for the full development of rheological properties in the recovered residue, especially in the case of modified binders (Hanz et al. 2010; Kadrmas 2006; Lewandowski 2010). Further, it was found that as the time of curing increases, a considerable component of the change in the rheology of the residue occurs because of oxidative aging. Moreover, the researchers suggest that the properties of the recovered residue from this procedure are more comparable to those of short-term aged binders rather than unaged binders. Thus, the residue is akin to rolling thin-film oven-aged material rather than unaged material. However, it should be noted that recovery or aging using the RTFOT is not applicable to surface treatment binders owing to the high temperatures involved, which are not representative of field conditions.

Further, (Kadrmas 2006) compared a distillation recovery method performed at 177ºC with the forced draft oven method for latex- and polymer-modified emulsions. The 177ºC distillation method is a modification of the method specified in ASTM D6997, with a 20-min hold at 177ºC. The evaporation method was found to produce residue that had undergone less polymer degradation than that obtained from the distillation method. However, the distillation procedure gives DSR results that are closely comparable to those of the original base binder. In addition, Method A was found to produce a stiffer residue than Method B. Both methods were determined to be repeatable.(Lewandowski 2010)

As part of the study described in this thesis, the effectiveness of these two low-temperature emulsion residue recovery methods in generating emulsion residue suitable for testing under a revised SPG specification was evaluated.

Surface Performance Grading Specification

The SPG specification for surface treatment binders in service was developed and initially field validated under TxDOT Project 0-1710 Superpave Binder Tests for Surface Treatment Binders (Barcena et al. 2002; Epps Martin et al. 2001; Walubita et al. 2004; Walubita and Epps Martin 2005b; Walubita et al. 2005a). Twenty-one commonly used TxDOT surface treatment binders, including nine grades of hot-applied asphalt cements, were tested in the development of this specification. For each emulsion, researchers evaluated five emulsion residue recovery methods (hot oven, rotavap, hot plate, distillation, and stirred can). The tests used in the specification were conducted using standard PG testing equipment; and the analyses were performance based and consistent with surface treatment mix design, construction, behavior, in-service performance, and associated distresses. The researchers identified the most appropriate emulsion residue recovery process and performed standard and modified PG binder testing. This led to the development of the SPG specification, including the associated grade selection process.

The testing methodology used for developing the SPG specification was adapted from the standard PG binder testing process. Unlike the standard PG system, the high and low pavement temperatures were calculated at the surface to reflect the critical conditions for surface treatment binder performance. Further, narrower temperature increments of 3°C were utilized. Binder SPG properties were determined for unaged and PAV-aged material to account for the critical first year of surface treatment binder performance. Rotational viscometer tests were conducted at several temperatures to determine the spraying temperatures for hot-applied asphalt cements. Further, DSR testing was performed only on unaged binders to reflect the critical conditions for newly laid surface treatments at high pavement temperatures. Finally, for low-temperature testing after PAV aging, the binder stiffness was measured at the short loading time of 8 s using the bending beam rheometer (BBR) equipment to simulate critical traffic loading conditions. The actual test temperature was used to determine the low-temperature SPG grade.

To develop the SPG specification, the measured binder properties were analyzed in conjunction with field performance ratings and the corresponding surface pavement temperatures were calculated using SHRP temperature models and the LTPPBind V2.1 database. Project information from 45 randomly selected HSs from the 2001 and 2002 TxDOT district surface treatment programs provided the basis for validation. Data were collected for factors that affected surface treatment performance including binders (types and associated suppliers), aggregates (types, gradations, and coating), environmental conditions, and traffic. The surface condition index (SCI) criterion was used for the performance evaluation of the HSs for one year after their construction, and a minimum acceptable SCI threshold of 70% was selected for rating the HSs. The predominant surface treatment distresses—aggregate loss and bleeding—associated with inappropriate material selection were monitored on each HS. Most of the materials used in these surface treatments were sampled onsite for laboratory testing and SPG grading. The stirred can method was used for recovering emulsion residue, as it was found to yield better results than the hot oven, rotavap, hot plate, and distillation processes, in terms of residue quantity, minimization of asphalt oxidation, maximization of water removal, and optimization of the recovery process time. Further, based on FTIR spectroscopy analysis, PAV aging was found to simulate one year of environmental exposure for surface treatments (Walubita et al. 2005a).

There was a good correlation between the SPG grade and observed performance for 78% of the HSs. The discrepancies between laboratory and field performance results were attributed to the SPG limits and grading criteria; poor material quality; and design, construction, quality control, and traffic factors. Based on the initial field validation, the spraying viscosity-temperature limit was increased to 205°C from 180°C to include some additional modified binders. Further, the G*/Sin δ high-temperature threshold value was decreased to 0.65 kPa to include binders with values insignificantly below 0.75 kPa demonstrating adequate field performance. Lastly, an increased temperature grade increment of 6°C was adopted for the lower temperature limit to ensure a consistent change in reliability at both high and low design temperatures. Eight standardized binder SPG grades were established for Texas conditions at 98% reliability. Table 1 shows the SPG specification proposed as part of TxDOT Project 0-1710.

Table 1: The Original Proposed SPG Specification (Walubita et al. 2004; Walubita et al. 2005a)

Only three binder grades are shown, but the grades are unlimited and can be extended in both high and low temperature directions using 3˚ or 6 ˚C increments, respectively.	**Performance Grade**											
	SPG 58				**SPG 61**				**SPG 64**			
	-10	**-16**	**-22**	**-28**	**-10**	**-16**	**-22**	**-28**	**-10**	**-16**	**-22**	**-28**
Average 7-day Maximum Surface Pavement Design Temperature, °C	<58				<61				<64			
Minimum Surface Pavement Design Temperature, °C	>-10	>-16	>-22	>-28	>-10	>-16	>-22	>-28	>-10	>-16	>-22	>-28
Original Binder												
Viscosity ASTM D 4402 Maximum: 0.15 Pa.s; Minimum: 0.10 Pa.s Test Temperature, °C	≤205				≤205				≤205			
Dynamic Shear, AASHTO T315/ASTM D7175 $\frac{G^*}{Sin\,\delta}$, Minimum: 0.65 kPa Test Temperature @10 rad/s, °C	58				61				64			
Pressure Aging Vessel (PAV) Residue (AASHTO PP1)												
PAV Aging Temperature, °C	90				100				100			
Creep Stiffness, AASHTO T 313/ASTM D6648 S, Maximum: 500 MPa m-value, Minimum: 0.240 Test Temperature @ 8s, °C	-10	-16	-22	-28	-10	-16	-22	-28	-10	-16	-22	-28

The researchers recommended that further validation, possibly with controlled test sections or pilot implementation projects, be performed to address some of the deficiencies and failures associated with the proposed SPG specification. The possibility of directly incorporating traffic and loading conditions into the binder SPG grade selection process was also suggested. Lastly, the researchers recommended that performance monitoring be carried out for more than one year to capture the full effect of traffic, environmental conditions, and the aging of the binder.

The SPG specification developed in TxDOT Project 0-1710 was further developed and field validated as part of NCHRP Project 14-17 Manual for Emulsion-Based Chip Seals for Pavement Preservation (Hoyt et al. 2010; Shuler et al. 2011). In addition, one new emulsion residue recovery method, namely, the force draft oven method was compared with the stirred can and hot oven methods to specify a standardized recovery method for use with the SPG specification. In this project, eight emulsions and five base binders were characterized using both the standard PG system (AI 2003) and the original SPG system (Barcena et al. 2002; Epps Martin et al. 2001; Walubita and Epps Martin 2005b; Walubita et al. 2005a) and some additional DSR and chemical tests. Notably, strain sweep testing was investigated in this project as a possible addition to the SPG system for evaluating strain tolerance and resistance to raveling of emulsion residues during curing and at early ages. Strain sweeps and their correlation with the sweep test, ASTM D-7000 (ASTM 2009), had been investigated elsewhere (Kucharek 2007) for evaluating the potential of emulsions to resist raveling during curing immediately after surface treatment construction.

At high temperatures, the base binders in every case exhibited lower test parameters ($G^*/\sin\delta$) than did the recovered residues. This was possibly due to the stiffening and aging of the residues during either the emulsification process or the emulsion residue recovery process. The BBR test results indicated that the base binders and the recovered emulsion residues had similar low-temperature properties. This could be due to deterioration of the polymer additive structure over time and with aging (Woo et al. 2006). All of the materials passed the PG (G*sin δ) criterion at the corresponding specified intermediate temperatures. In general, the PG grades were consistent for the base binder and the residues from both stirred can and hot oven recovery methods, as were the SPG grades.

Chromatograms obtained from gel permeation chromatography (GPC) for all of the emulsion residues revealed that both the stirred can and hot oven recovery processes completely removed water from the emulsions, while the force draft oven method resulted in residue with a small detectable amount of moisture. The carbonyl areas calculated from FTIR spectra for the five laboratory emulsions indicated that the recovered binders were all slightly more oxidized than the base binders were. This oxidation could have occurred during emulsification or during the emulsion residue recovery process. Further, the oxidative effects of the different recovery methods were found to be similar. When comparing the DSR data by recovery method, the analysis results statistically grouped the recovery methods of stirred can and hot oven together, and the base binder (no recovery) was grouped separately for the emulsions with base binders available. Both recovered residues were stiffer, with larger values of log (G*/sin δ), than the base binders, but not stiff enough to change the high-temperature PG grade. With smaller temperature increments, the high-temperature SPG grade did change to a larger value for four of the emulsions. The recurring result from all of the analyses of the BBR measurements was that the recovery method (with base binders included as no recovery) did not practically affect the response variables S or m-value for any of the recovered residues. This result seemed to indicate that, after PAV aging and consequent oxidation, the polymers and additives no longer had an effect on the stiffness properties.

Table 2: Modified SPG Specification (Hoyt et al. 2010)

Only three SPG grades are shown, but the grades are unlimited and can be extended in both directions of the temperature spectrum using 3° and 6°C increments for the high temperature and low temperature grades, respectively.	**Performance Grade**											
	SPG 64				**SPG 67**				**SPG 70**			
	-12	**-18**	**-24**	**-30**	**-12**	**-18**	**-24**	**-30**	**-12**	**-18**	**-24**	**-30**
Average 7-day Maximum Surface Pavement Design Temperature, °C	<64				<67				<70			
Minimum Surface Pavement Design Temperature, °C	>-12	>-18	>-24	>-30	>-12	>-18	>-24	>-30	>-12	>-18	>-24	>-30
Original Binder												
Dynamic Shear, AASHTO T 315/ASTM D7175 $\frac{G^*}{Sin\,\delta}$, Minimum: 0.65 kPa Test Temperature @10 rad/s, °C	64				67				70			
Shear Strain Sweep % strain @ 0.8G_i*, Minimum: 25 Test Temperature @10 rad/s linear loading from 1-50% strain, 1 sec delay time with measurement of 20-30 increments, °C	25				25				25			
Pressure Aging Vessel (PAV) Residue (AASHTO PP1)												
PAV Aging Temperature, °C	100				100				100			
Creep Stiffness, AASHTO T 313/ASTM D6648 S, Maximum: 500 MPa m-value, Minimum: 0.240 Test Temperature @ 8s, °C	-12	-18	-24	-30	-12	-18	-24	-30	-12	-18	-24	-30
Shear Strain Sweep G_i*, Maximum: 2.5 MPa Test Temperature @10 rad/s linear loading at 1% strain and 1 sec delay time, °C	25				25				25			

Based on these results, a modified SPG emulsion residue specification was developed (Hoyt et al. 2010). The strain sweep thresholds were selected to reflect the significantly different performance of two of the emulsions tested. Further, based on the recovery methods evaluated in their project, the researchers recommended the stirred can emulsion residue recovery method for use with this proposed specification.

Further, they recommended that strain sweeps be performed with the DSR on curing and unaged emulsion residues to evaluate strain resistance and stiffness development. These tests could be used to predict when emulsion-based surface treatments will develop enough stiffness to be opened to traffic. Strain sweeps could also be used to assess a material's resistance to raveling, both in newly constructed surface treatments and after the critical first seasons of weather and aging. However, the appropriate test parameters and the performance criteria should be refined further.

Researchers recommended that further field validation of the SPG specification thresholds, shown in Table 2, in regions other than Texas is needed before the specification for SPG can be approved and used at a national level. Moreover, further evaluation of the available emulsion residue recovery methods was suggested to determine which of these most closely simulates emulsion residue in the field and to address possible destruction or change in any polymer networks in many commonly used modified emulsions during recovery. The possibility of replacing low-temperature testing using the BBR with an alternative test which measures G* at low temperatures directly was also recognized as a recommended improvement.

Exclusive Use of DSR for Rheological Testing

The SPG specification, as in the PG specification, utilizes rheological tests for the characterization of material performance. In the PG and SPG specifications, the DSR and the BBR are used for evaluating the high-, intermediate- and low-temperature behavior of aged and unaged hot-applied asphalt cement. The performance-based properties measured in these tests are used to ensure that the binder is stiff and elastic enough to resist permanent deformation due to traffic loading in the initial stages of its life, and to ensure that the binder is not too brittle at intermediate and low temperatures. In addition to these standard tests, DSR strain sweeps can be used to evaluate strain tolerance and resistance to raveling during curing of emulsions and at early ages for both hot-applied asphalt cements and emulsion residues. Further, the multiple stress creep recovery (MSCR) test performed with the DSR can be used to study the creep and recovery behavior of modified binders and to evaluate resistance to rutting and bleeding. Applying the principle of time-temperature superposition, the frequency sweep curves obtained using the DSR at intermediate temperatures can be utilized to obtain the properties of binders at low temperatures (Marasteanu and Clyne 2006). These tests can be applied to both hot-applied asphalt cements and emulsion residues. Thus, a system to characterize surface binders entirely using the DSR may be developed.

Based on discussions at the Emulsion Task Force meetings of the Federal Highway Administration (FHWA) Perpetual Pavement Expert Task Group, the possibility of the exclusive use of the DSR to characterize surface treatment binders was first explored as part of the Asphalt Research Consortium in conjunction with the

Federal Lands Study Using Polymer-Modified Asphalt Emulsions in Surface Treatments, both sponsored by FHWA (Hanz and Bahia 2010; Johnston and King 2009). The University of Wisconsin tested a base asphalt cement at four different aging conditions (unaged and aged using the RTFO, PAV, and two times PAV (2PAV)) in the standard BBR at -12 ºC and in the DSR at 10 ºC in frequency sweeps at 10 and 20 Hz to match the frequency predicted for equivalent creep stiffness in bending and dynamic shear stiffness from the SHRP project (Anderson 1994). Additionally, Paving, Roofing, and Industrial (PRI) Asphalt Technologies, Inc. tested four corresponding emulsion residues recovered by the force draft oven method in the standard BBR at -12 ºC and in the DSR at 10 ºC in a frequency sweep at 10 Hz. These emulsions included two latex modified materials (CRS-2LM, RALUMAC LMCQS-1h), a CRS-2, and a PASS emulsion. The complex modulus (G*) and phase angle (δ) at these frequencies were compared to the stiffness and m-value after 60 s of loading (S(60) and m(60)). The appropriate frequency for testing that enables the comparison of the DSR parameters with the BBR parameters was determined using Equation 1 (Anderson 1994; Hanz and Bahia 2010):

$$T_d = \left[\frac{1}{273 + T_s} - \frac{2.303 \times R \times \log(t_s \times \omega)}{250{,}000}\right]^{-1} - 273 \qquad \text{Equation 1}$$

where:
T_d = test temperature for dynamic testing at frequency ω, °C
T_s = specified temperature for creep testing, °C
R = ideal gas constant, 8.31 J/°K-mol
T_s = specified creep loading time, s
ω = dynamic testing frequency, rad/s

Estimates of S(60) and m(60), obtained from Equations 2 and 3, were compared to actual BBR measurements (Anderson 1994):

$$S(t) \approx \frac{3G^*(\omega)}{[1 + 0.2\sin(2\delta)]}\ as\ t \to \frac{1}{\omega} \qquad \text{Equation 2}$$

$$m = \frac{d(\log G^*)}{d\ (\log \omega)} \qquad \text{Equation 3}$$

where:
S(t) = creep stiffness at time, t, Pa
m = slope of G* vs. frequency plot at a given frequency
G*(ω) = complex modulus at frequency ω, Pa
δ = phase angle at frequency ω, Pa

Strong correlations were found in the comparison of measured BBR low-temperature stiffness parameters (S and m-value) and those estimated from measured DSR parameters at the specified temperature and frequency.

Additionally, the Western Research Institute (WRI) is conducting research evaluating the possible exclusive use of the DSR for characterizing surface treatment binders. Their work is focused on directly measuring low-temperature properties in the DSR using smaller 4-mm plates (WRI 2009). With this geometry, a smaller 25 mg sample can be tested in a temperature range from -40º to 60ºC. Further, the DSR method does not require the samples to be heated to a high temperature such as 135 ºC for molding. Researchers proposed that the shear stress relaxation modulus obtained from a step strain test using the DSR is similar to the BBR parameter (creep stiffness) as a measure of the stiffness of the asphalt tested (Sui et al. 2011). The stress relaxation modulus was interconverted by using the generalized Maxwell model from DSR dynamic frequency sweep data. A strong linear relationship was observed between the flexural creep stress data from BBR testing and the shear stress relaxation data from the DSR testing of 14 validation site binders, one validation site core binder, and one Material Reference Library binder. Correlation was also found between the respective apparent relaxation rates. The results indicate that the use of 4-mm parallel plates is reliable, fast, and simple, and allows for the analysis of the low-temperature properties of emulsion residues (Sui et al. 2010). This work should provide further evidence that time-temperature superposition holds across the entire spectrum of conditions of interest. Further, it validates the estimation of low-temperature properties from DSR intermediate temperature properties based on the University of Wisconsin study(Hanz and Bahia 2010).

The DSR has also recently been utilized for evaluating binder-aggregate compatibility. Kanitpong and Bahia (2007) observed that the separation of the binder from the aggregate surface can occur either because of cohesive failure within the binder or because of the adhesive failure of the bond between aggregate and binder. The type of failure that occurs can be ascertained by examining the failure surface or binder remnant on the substrate after testing using the pneumatic adhesion tensile testing instrument (PATTI) as described subsequently. Bikerman (1947) theorized that, for liquid adhesives, cohesive failure is far more likely than adhesive failure unless the bond between the adhesive and the solid surface is very weak. Bikerman developed an equation for the evaluation of tackiness, the resistance offered by liquid adhesive joining two solid surfaces to normal tensile force; this equation quantifies the viscous resistance of the thin film of adhesive moving in the slit between the two solid plates it joins, at a rate determined by the rate of separation of the plates (Cho et al. 2005). Researchers at the University of Wisconsin-Madison (Kanitpong and Bahia 2007) extended this theory to develop a method to measure the thin film tackiness of asphalt using the DSR. Kanitpong and Bahia confirmed that failure is indeed more common within the binder layer than between the binder layer and aggregate using their Tensile Strength Ratio Test. This justifies the use of the DSR to test binders for cohesive strength in the absence of aggregates. Further, the tack test was found to be very repeatable for testing modified and unmodified binders. Tackiness was found to decrease with increasing temperature. Furthermore, the tack factor of polymer-modified binders was observed to be considerably higher than that of the original binder. However, the addition of anti-stripping agents did not improve tackiness. Because of this, the research team concluded that the improvement in bond strength of binders containing these additives, as observed during the bitumen bond strength (BBS) tests described subsequently, was mainly due to adhesion and not cohesive properties. The tack test was found to have good repeatability, and its results were well correlated with tensile strength results obtained using the AASHTO T 283 method for HMA (Zofka et al. 2005).

Recent DSR results from the University of Wisconsin include a recommendation of the MSCR test at high temperatures to evaluate resistance to bleeding. The MSCR can be used to characterize elastic recovery (recoverable strain) and J_{nr} (compliance) of polymer-modified binders more accurately than the standard DSR test. The lower the J_{nr} value for a residue, the greater is its resistance to bleeding. It has been proposed that MSCR results be used to eliminate the practice of grade bumping in the PG system based on DSR results to account for slow speed loading and high traffic volumes on flexible pavements. Kadrmas (2009) has suggested that the MSCR test can be modified for use with emulsions by testing residue not subjected to RTFO aging. Kadrmas proposed different J_{nr} levels corresponding to different traffic loading ($J_{nr} \leq 4$ kPa^{-1} for standard traffic; $J_{nr} \leq 2$ kPa^{-1} for heavy traffic; $J_{nr} \leq 1$ kPa^{-1} for very heavy traffic).

Moreover, in the last decade, the elastic recovery test has been used in conjunction with the tests included in the PG specification to characterize modified binders. The elastic recovery test has been found to be useful in determining the presence of modifiers in the binder and binder quality. However, the standard methods for the measurement of elastic recovery in binders are time consuming and prone to user errors (Clopotel et al. 2011). Researchers studied the relationship between percent recovery from MSCR testing and elastic recovery measured using the standard ductilometer and found considerable correlation between the MSCR results obtained at PG temperatures and ductilometer elastic recovery results at 25°C (Christensen 2008). Clopotel et al. (2011) developed a simple method for measuring the elastic recovery of binders using the DSR. Using 8-mm parallel plates in the DSR, samples aged in the rolling thin film oven test (RTFOT) were first subjected to a constant strain for 2 min and then to constant shear stress for 1 h or 30 min. The test was performed at 25°C and the experimental conditions were defined to match those of the standard elastic recovery test. The results from the DSR/MSCR were well correlated with the ductilometer results. The researchers further attempted to correlate the elastic recovery measurements from the DSR with binder rutting resistance results obtained from the MSCR test and various binder fatigue resistance results. The elastic recovery values obtained from the MSCR test changed logically with some of the important binder properties. However, the DSR elastic recovery results were not recommended as a good replacement to any of the standard binder performance properties they were compared with, owing to large variability in results. The DSR/MSCR test can be used to replace the standard method of measuring elastic recovery in binders, and can be used to complement other PG properties aimed at controlling binder performance.

Binder-Aggregate Compatibility/Adhesion

Aggregate loss is among the most common problems associated with surface treatments (Shuler 1990). The ability of asphalt binder to properly coat and bind with aggregate plays a major role in the performance of surface treatments. Aggregates and binders bond through mechanical, chemical, electrostatic, and adhesive mechanisms. Aggregate properties such as porosity, surface texture, mineralogy, and surface chemistry as well as binder characteristics such as chemical composition, surface tension, and viscosity at the time of application influence the effectiveness of the binder–aggregate bond (Smith et al. 1995). Short-term aggregate loss can be the result of insufficient binder quantity or low binder and substrate temperatures at the time of construction. Conversely, long-term aggregate loss is related to decreased adhesion between the binder and the aggregate or reduced cohesion within the binder over time. The loss in adhesion and cohesion is, in turn, associated with oxidative hardening and resultant brittleness in the binder, reduced binder resilience, and stripping. Aggregate retention may therefore be improved by using binders with higher failure strain or by using anti-oxidative additives or polymer modifiers. For emulsions, the type of emulsion (cationic/anionic) and the associated setting processes affect the bonding.

ASTM D 244 specifies one of the many methods for verifying the compatibility of binder and aggregate (ASTM 2009). In this method, the ability of emulsified asphalt to continue coating the aggregate during a 5-min mixing cycle is observed, and the resistance offered by the coating to wash-off is determined. This method is qualitative as it involves the visual inspection of the aggregate sample for coating.

Another method studied by (Kanitpong and Bahia 2007) measures the pull-off tensile strength or the BBS of binders with and without anti-stripping additives using the PATTI. This method is a modification of the method specified in ASTM D 4541 (ASTM 2009), which describes the evaluation of the pull-off strength of a coating system from metal substrates. The PATTI was originally used by Youtcheff and Aurilio in 1997 with a ceramic pullout stub held on a glass plate to evaluate the moisture susceptibility of asphalt binders. Kanitpong and Bahia modified the stubs to better control the film thickness and specified a conditioning temperature of 25ºC. Further changes were made to the testing conditions and equipment—in particular, the design of the pull-out stub - to develop the BBS test as it is currently performed (Meng et al. 2010).

Further, (Hanz et al. 2008) modified the BBS test—that had previously been utilized for testing binder-aggregate interaction in hot-applied asphalts—for application in emulsion testing. To determine adhesive strength, emulsion is applied to a pull stub placed on the aggregate surface. Then, using air pressure in the PATTI, a consistent tensile force is applied to separate the binder and the aggregate surface. The researchers calculated the pull-off tensile strength of the binder by measuring the pressure at which the pull stub debonds from the aggregate surface (Santagata et al. 2009). The failure surface is examined for signs of adhesive failure as opposed to cohesive failure, which occurs entirely within the binder layer.

Researchers from the University of Wisconsin (Bahia et al. 2009) conducted the BBS test to determine the factors that affect the pull-off tensile strength. The researchers studied the effects of two different curing temperatures, three different aggregate types, and two emulsion types on the bond strength. They found that curing temperatures had no effect on the development of bond strength between the binder and aggregate. Further, granite and sandstone were found to develop a stronger bond with the binder than dolomite. In addition, polymer-modified cationic rapid-setting type emulsion always underperformed in comparison to unmodified binder. At a 90% confidence level, the curing conditions and the aggregate type were found to be statistically significant in the development of BBS, while the surface roughness of the aggregate was found to be statistically insignificant. In addition, the BBS determined was compared with the performance of the binder-aggregate combination in the sweep test (ASTM 2008). For both limestone and granite aggregate, aggregate loss was found to decrease with increasing pull-off tensile strength. In a related study, it was concluded that the BBS test is both repeatable and reproducible and can effectively measure the effects of moisture on asphalt-aggregate bond strength (Moraes et al. 2011).

The BBS test was applied to emulsion residues by adjusting the thickness of the pull stub and measuring bond strength for different curing times and aggregate substrates. As expected, samples with a longer curing time (24 h) exhibited increased tensile strength as compared to samples with a shorter curing time (2 h); however, both curing times were found to be insufficient for the emulsion to attain the maximum possible adhesive strength. Moreover, emulsions cured on granite substrates were found to have achieved higher adhesive strength than those cured on limestone substrates. In addition, the presence of water in the emulsion residue was found to retard adhesive properties at both curing times. In another study, the BBS test revealed that the addition of wax-based warm mix additive reduces the dry cohesive strength of asphalt binders (Wasiuddin et al. 2011).

Researchers compared the results of the BBS test with DSR strain sweep results to verify correlation between bond strength and the $G^*/\sin\delta$ DSR parameter and with sweep test results that measure aggregate loss (ASTM 2008; Miller et al. 2010). DSR strain sweep results were found to be effective for validating BBS results. Further, comparison with sweep test results indicated that curing temperature, curing relative humidity, aggregate type, and curing time are the major factors affecting adhesion for various binder-aggregate combinations tested using the PATTI. The pull-off strength results were dependent on other test parameters such as binder type and loading rate. The researchers also proposed a preliminary BBS specification limit of 100 psi. Based on these and other results, the BBS test appears to be a simple, effective, and repeatable technique for measuring the adhesion between emulsions and aggregate (Copeland 2007).

Banerjee et al. (2010) designed a different aggregate pull-out test to examine binder-aggregate bond strength. In this test, aggregate shaped into half-inch diameter cores is embedded in emulsion poured onto a metal plate and contained by a Nitrile Buna Rubber O-ring (internal diameter 4 in and thickness 3/32 in). The test was performed using four types of aggregates, with three different aggregate placement delay times (5, 10, and 15 min), various temperatures (32 ºF, 70 ºF, and 140 ºF), and times (15, 60, 120 min, and 24 h) to pull out. The bond strength is estimated using the measured force and the cross-sectional area of the cylindrical aggregate specimen. The researchers found that the bond strength is highest at moderate temperatures during pullout and with lower aggregate placement delay time. Further, for a given aggregate placement delay time, bond strength increased as the time to pull out or the time available for curing increased. Moreover, a lower aggregate placement delay time resulted in higher binder-aggregate bond strength. This test highlights the importance of the curing time as a factor affecting the final strength of the surface treatment and may be useful for measuring binder-aggregate adhesion just after construction.

Surface energy has long been considered an important parameter toward understanding adhesion in HMA (Ensley et al. 1984). The energy released during the interaction of aggregate with binders can be measured using a sensitive microcalorimeter. Previous research has indicated an extended release of energy after initial binder-aggregate contact (Hefer 2005), that can be attributed to bond formation and propagation. It has been suggested that the initial peak in surface energy reflects the adsorption of an initial layer of binder molecules onto the aggregate surface. Contact angle techniques, vapor sorption techniques, force microscopy, and microcalorimetry are among the popular methods used to quantify binder-aggregate bond strength (Hefer and Little 2005). Contact angle techniques have been found to be the most simple of these techniques; in contrast, vapor sorption, which may be the best approach for determining surface energy, is time consuming. Inverse gas chromatography, which is similar to dynamic vapor sorption, has been identified as a strong candidate for the characterization of surface energies at different temperatures.

Aging

The use of high temperatures in the laboratory aging methods applied to HMA and surface treatment binders may be problematic when testing binders containing latex additions or polymers (Kadrmas 2007). The method specified in the standard EN 14895 has been recommended (Gueit et al. 2007) to simulate medium-term aging—that is, to simulate the conditions 6 to 12 months after construction— in emulsions. In this method, a thin film of residue is maintained for 24 h at ambient temperature, an additional 24 h at 50°C, and finally 24 h at 85°C. Gueit et al. (2007) also simulated several years of aging by PAV aging the binder for 65 h at 85°C. This method was effective in retaining the polymer components of modified binders, as detected using UV microscopy and infrared absorption spectroscopy. However, the elastic recovery and cohesion of the polymers were found to deteriorate during PAV aging, which does not correspond to the field behavior of emulsions. These changes will be considered in this project for emulsion residues.

An alternative method of aging, not proposed for use in this project, is using ultraviolet (UV) irradiation. Huang et al. studied the response of asphalt, divided into Corbett fractions, to UV aging (Huang et al. 1995). FTIR revealed that all the fractions had undergone oxidation—the phenomenon associated with aging and deterioration in binder properties. This finding is highly pertinent to emulsions and other surface treatment binders that are regularly exposed to the UV light in sunlight. Further, the researchers found that exposure to UV light results in extensive deterioration in the low-temperature performance of binders, while the high-temperature performance is almost unchanged (Li et al. 2008). On the other hand, a 1996 TTI study (Button 1996) investigated the effects of surface seals on the oxidative hardening of underlying HMA layers and revealed that UV light penetrates asphalt binders only a few microns and, therefore, does not contribute materially to the hardening of the uppermost layer of asphalt concrete.

The existing methods for simulating aging in binders function on the assumption that aging occurs in response to exposure to very high temperatures and to oxygen at the time of production, during construction, and over the long-term. Given that UV aging is more likely in thinner bituminous layers such as those formed by the application of emulsions, it might be necessary to consider the effect of photo aging and thermal aging to characterize binders. Several researchers (Durrieu et al. 2007; Mouillet et al. 2008; Wu et al. 2010) have incorporated UV irradiation into the laboratory aging process for binders by using a UV oven. Typically, samples are first RTFOT-aged, before being subjected to UV aging and aging in the PAV. Then, to isolate the effect of UV radiation on the binder, identical samples are aged using only RTFO and PAV. FTIR spectra are then utilized to study oxidative aging due to exposure to UV light. The extent of aging due to photo oxidation has been found to be significant, resulting in a more viscous residue than in the case of only thermal aging. Aging due to photo oxidation also increased with the intensity of the UV light (Wu et al. 2010). Notably, 10 h of exposure to UV radiation has been found to cause oxidation equivalent to that after RTFOT and PAV aging or that reached after one year of service in the field.

Summary

This literature review described several methods for the evaluation and characterization of surface treatment binders. Previous studies have identified aggregate loss and bleeding as the most commonly observed distresses in surface treatments (Epps Martin et al. 2001; Walubita et al. 2004). These distresses could be the result of improper construction, design, or materials. The aim of developing an SPG specification is to specify standard test methods for the evaluation and characterization of the surface treatment binders in service that include both hot-applied asphalt cements and emulsion residues. Based on the information from the literature review, two warm oven residue recovery methods were identified for evaluation as part of this study. Moreover, the PAV method, which is the laboratory method included in the PG specification for simulating long-term aging, was selected for use in the SPG specification.

The rheological properties of the binders that are related to the primary distresses observed in the surface treatments were evaluated through a combination of existing SPG tests and additional tests using the DSR. The stiffness of the binder at the high- and low-temperature limits of performance were measured using the DSR test and the BBR test, respectively.

A minimum value is specified for $G^*/\sin\delta$ to ensure a binder that is stiff enough at high temperatures in order to resist deformation and bleeding. A maximum value and minimum value are prescribed for the BBR S and m-value, respectively, to ensure that the binder is not too stiff at the low temperature limit, causing fracture and aggregate loss.

The DSR strain sweep test is included in the SPG specification to characterize the non-linear viscoelastic behavior of the binder, which could be related to aggregate loss due to the loss of strength at a critical strain level (reduction in G^* with increasing strain). Further, the DSR MSCR test was identified as a useful method for characterizing the binder properties of recoverable strain and creep compliance that are related to bleeding. In addition, the DSR frequency sweep test was selected for the measurement of G^* and δ at an intermediate temperature, in order to predict the low-temperature rheological binder properties (S and m-value) that are normally obtained using the BBR test. This DSR method was evaluated as a replacement for the traditional BBR test for the characterization of the binder properties associated with brittleness and aggregate loss at low temperatures. Using a combination of methods proposed in the literature to quantify the rheological and chemical properties of surface treatment binders, as summarized in Table 3, this study aimed to develop a comprehensive SPG specification.

Table 3: Characterization of Surface Treatment Binders

Property		Test	Conditions	Parameter
Emulsion Residue Recovery and Evaluation	Residue Recovery	*Forced Draft Oven*	60 g; 24 h at 25°C and 24 h at 60°C	Amount Residue Recovered
		Texas Oven	0.015”; 6 h at 60°C	
	Water Removal and Oxidation of Recovered Residue	*GPC*		Peak at a time of 35 to 37.5 min in chromatogram
		FTIR		Carbonyl area
Aging Simulation	PAV aging for 20 h at 2.1 MPa pressure and 100°C temperature ≈ 1 summer + 1 winter in field (Walubita et al. 2005a)			
Aggregate Loss	High-Temperature Stiffness	*DSR*	High temp; 10 rad/s for unaged binders	G*/Sin δ
	Strain Tolerance	*Shear Strain Sweep*	25°C; 10 rad/s linear loading from 1-50% strain, 1 sec time delay & 20-30 increments for unaged binders	Percent strain at 0.8G*
	Strain Tolerance with Age	*Shear Strain Sweep*	25°C; 10 rad/s linear loading, 1% strain, 1 sec time delay for PAV-aged binders	G_i*
	Low-temperature Stiffness	*BBR*	Low temp; 8s for PAV-aged binders	S and m-values
	Replacement for BBR Test	*DSR Frequency Sweep*	6°C, 10°C, 15°C; 0.1-20 Hz; 1% strain, 10 s time delay for PAV-aged binders	G* and δ
Bleeding	High-Temperature Stiffness	*DSR*	High temp; 10 rad/s for unaged binders	G*/Sin δ
	Elasticity	*MSCR*	High temp High temp at 3.2 kPa for unaged binders	J_{nr}, J_{nr} ratio % recoverable strain

CHAPTER III

EXPERIMENTAL DESIGN

The revision and validation of the SPG specification involved the following main tasks—HS selection, field performance monitoring, laboratory testing, and data synthesis. The work plan shown in Figure 1 illustrates the order and components of these tasks. The first task of highway section selection involved the identification of sections with surface treatments placed in 2011 as well as the selection of sections placed in 2002 during TxDOT Project 0-1710 for performance monitoring. Each of these tasks is discussed in further detail in this chapter. Field performance monitoring involved the inspection of the selected highway sections (HSs) for visible surface distresses and pavement performance evaluation. The extensive laboratory-testing program carried out as part of this study involved the evaluation of emulsion recovery methods, exploration of the exclusive use of the DSR to characterize surface treatment binder performance, and other chemical and rheological tests recommended for inclusion in a revised SPG specification.

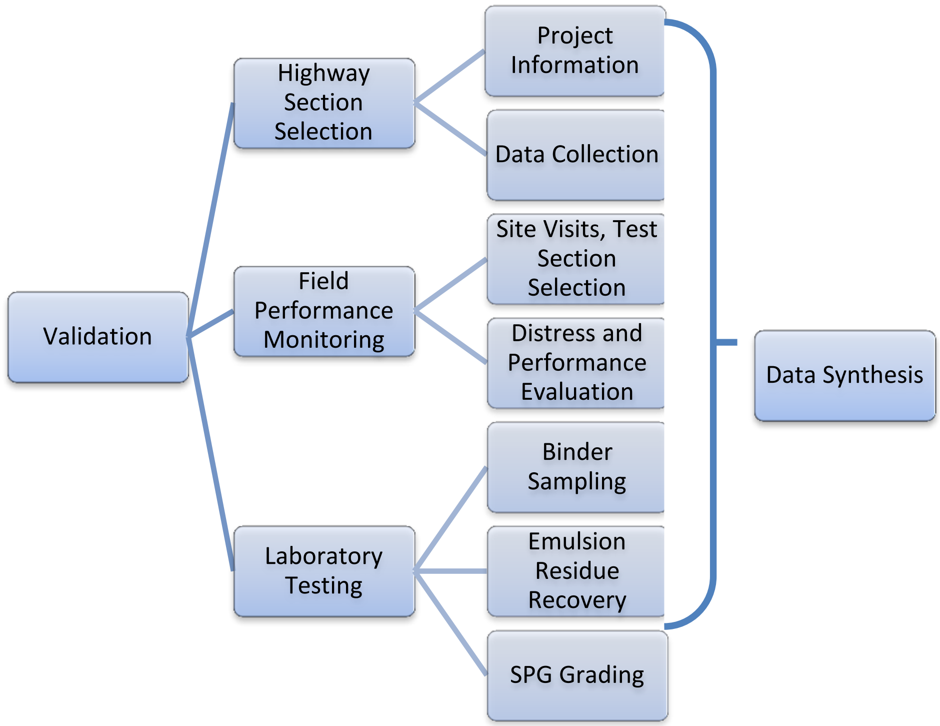


Figure 1: Methodology

Highway Section Selection

The highway section selection task was composed of two parts. The first involved the identification of 10 sections for performance monitoring from the 45 field sections studied in TxDOT Project 0-1710. In the second part of this task, researchers selected 30 field sections with commonly used TxDOT surface treatment binders for the extensive laboratory testing to be performed later in the study. The TxDOT Pavement Management Information System (PMIS) database was reviewed for each of the previous TxDOT 0-1710 sections to aid in determining whether work has been performed on the section. If no treatments have been placed since the original treatment, these sections were chosen for re-inspection using the visual survey method developed in TxDOT Project 0-1710. A preliminary review of the 45 sections showed that the average TxDOT PMIS Condition Scores for the sections ranged from 99.4 (indicating a high probability that the section has been sealed again), to a low of 69.2 (indicating that it has probably not received additional treatment). The sections included in the preliminary review are shown in Table 4, and the average Condition Scores suggested that many of these sections were still in service.

Table 4: Status of Previous TxDOT 0-1710 Field Sections Based on Preliminary Review.

0-1710 Number	*Highway*	*Length (mi)*	*District*	*Binder Type*	*Aggregate Type*	*Aggregate Grade*	*Construc -tionDate*	*2010 Condi tion Score*
20	BU 181G	2.5	Corpus	AC-15P	Limestone	Gr4	4/29/2002	86.5
30	FM 1001	8.94	Atlanta	CRS-2H	Lightweight	Gr4	5/17/2002	99.4
31	FM 114	5.35	Atlanta	CRS-2H	Lightweight	Gr4	4/22/2002	78.8
23	FM 1351	10.6	Corpus	AC-15P	Limestone	Gr3	4/17/2002	94.8
29	FM 1402	11.85	Atlanta	CRS-2H	Lightweight	Gr4	5/14/2002	77.6
3	FM 1617	1.5	Lufkin	AC-15-5TR	Lightweight	Gr4	9/10/2001	82.2
21	FM 627	7.57	Corpus	AC-15P	Limestone	Gr3	4/12/2002	89.1

Performance monitoring was completed for 16 field sections from the TxDOT Project 0-1710 at the beginning of the study in Spring 2011. Those sections that received additional surface treatments or overlaid since construction were eliminated from the study. The sections from the TxDOT Project 0-1710 that were included in this study are listed in Table 5.

Table 5: Previous TxDOT 0-1710 Field Sections Selected for Evaluation

0-1710 ID	Highway	Length (mi)	Location (Temp C)	District	County	Binder Type	Aggregate		Traffic		Date of Construction
							Type	Gradation	ADT	Speed	
HS 3	FM 1617	1.5	E (66-16)	Lufkin	Trinity	AC15-5TR	Lightweight	Gr 4	<3000	50	9/10/2001
HS 9	FM 318	2	E (65-12)	Yoakum	Lavaca	CRS-2P	Limestone	Gr 4	450	50	4/17/2002
HS 10	US 83	17.73	E (66-08)	Pharr	Zapata	AC15-5TR	Gravel	Gr 4	4800	>50	4/15/2002
HS 11	US 281(A)	2.96	E (66-08)	Pharr	Brooks	AC15-5TR	Limestone	Gr 4	9800	>50	4/15/2002
HS 12	US 281(B)	8	E (66-08)	Pharr	Brooks	AC15-5TR	Limestone	Gr 4	10,100	>50	4/15/2002
HS 13	FM 2926	11	W (67-20)	Abilene	Callahan	AC15-5TR	Limestone	Gr 3	<3000	50	5/22/2002
HS 14	SH 29	9.67	W (66-16)	Austin	Burnet	AC15-5TR	Sandstone	Gr 4	5000	>50	5/16/2002
HS 18	FM 3405	7.75	W (66-16)	Austin	Williamson	AC15-5TR	Sandstone	Gr 4	<3000	>50	5/20/2002
HS 19	SH 72	12.47	E (65-11)	Corpus	Karnes	AC-15P	Limestone	Gr 4	1900	>50	4/29/2002
HS 21	FM 627	7.57	E (65-11)	Corpus	Karnes	AC-15P	Limestone	Gr 3	130	>50	4/12/2002
HS 23	FM 1351	10.6	E (65-11)	Corpus	Goliad	AC-15P	Limestone	Gr 3	30	<50	4/17/2002
HS 24	US 385	23.6	W (67-18)	El Paso	Brewster	PG 76-16	Limestone	Gr 3	331	>50	4/23/2002
HS 28	FM 192	25.2	W (66-18)	El Paso	Hudspeth	PG 76-16	Limestone	Gr 3	213	>50	7/1/2002
HS 38	FM 212	8.3	W (65-23)	Lubbock	Lynn	AC10-2% Latex	Gravel	Gr 4	260	70	7/17/2002
HS 40	SH 152	6.4	W (65-26)	Amarillo	Gray	AC15-5TR	Limestone	Gr 4	<3000	70	6/10/2002
HS 44	SH 302(B)	18	W (68-18)	Odessa	Winkler	AC5-2% Latex	Limestone	Gr 3	2000	70	8/14/2002

In addition to the previously identified field sections still available from TxDOT Project 0-1710, new field sections to be constructed in 2011 were also identified and selected. These sections were chosen on the basis of proposed surface treatment plans, submitted by TxDOT districts, in areas where the district was willing to participate in establishing a new field section to be monitored by this study. The selected HSs are located in 5 of the 25 Texas districts and covered a range of materials, environmental, and traffic conditions so that SPG specification proposed as part of this study is valid for the entire array of Texas conditions. A total of 30 new sections were established during the study; all of these sections received single surface treatments, and 5 different types of binders were used in these treatments. The factors considered in selecting these sections were the binder or modifier type, aggregate type, treatment type, and Texas environmental zone. Each selected section was evaluated in terms of the surface condition index (SCI) defined in TxDOT Project 0-1710. For each highway section, the researchers also collected information on the traffic level, binder application rate, aggregate gradation and application rate, existing pavement surface, weather during construction, age, and extreme surface pavement temperatures used to select appropriate SPG grade. Some of the factors (binder type and aggregate type) have been evaluated in TxDOT Project 0-1710 using most of the same proposed field evaluation tools and laboratory evaluation tests. The performance monitoring data collection was carried out two times on each of the new field sections: once at or soon after construction and then after the first summer and winter.

The binder type is considered the most significant factor influencing surface treatment performance in relation to the SPG specification, followed by the environment, aggregate type, and traffic. For each factor, the following number and names of levels are shown in Figure 2: five binder types (B1 to B5), five environmental conditions (WW, DW, DC, WC, and M), eight aggregate types (A1 to A7), and three traffic volume categories (T1, T2, and T3). Each factor and the associated levels are discussed subsequently.

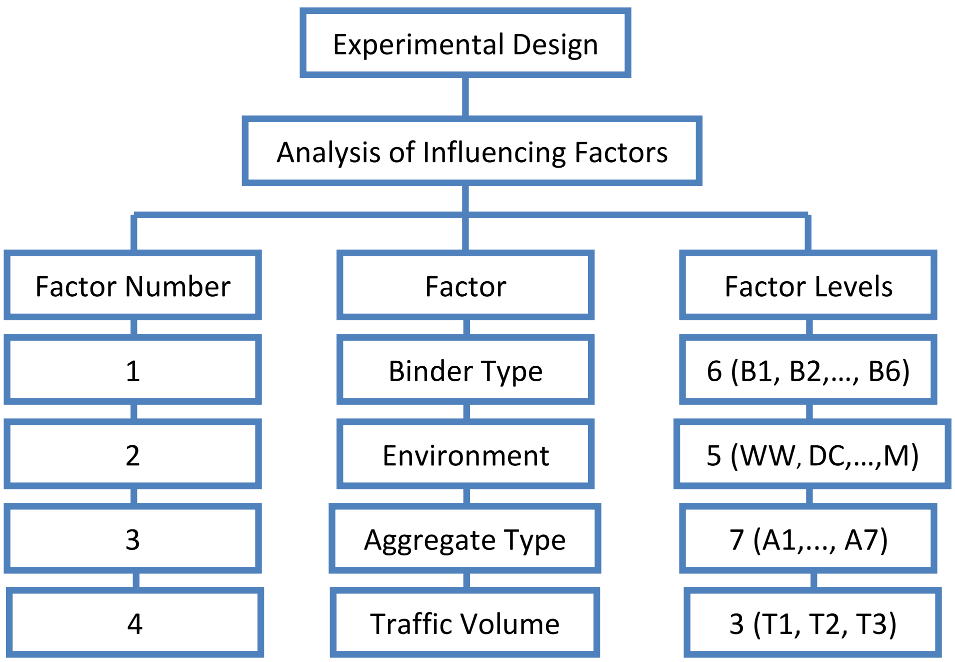


Figure 2: Experimental Design

These factors and the field evaluation tools used in this study are discussed in more detail subsequently.

Binder Types

Binder type was the primary factor in both the development and initial validation process of the SPG specification. The experimental design samples the two most commonly used emulsions and four most commonly used hot-applied asphalt cements (Table 6) utilized by TxDOT based on the 2009 TxDOT statistics and the feedback received from the districts. The two emulsions and three hot-applied asphalt cements represent 80% or more of the materials used by TxDOT by material type. Two suppliers for CRS-2, AC15P, and AC10 and three suppliers for CRS-2P and AC20-5TR were proposed to capture between 61 and 94% of surface treatment applications consisting of each material type.

Table 6: Binder Types

#	Designation	Binder	Brief Description
1	B1	CRS-2	Cationic, rapid setting, high viscosity emulsion
2	B2	CRS-2P	Cationic, rapid setting, high viscosity emulsion modified with a polymer
3	B3	AC10	Asphalt cement with 1000 poises viscosity at 60°C
4	B4	AC15P	Asphalt cement with 1500 poises viscosity at 60°C, modified with a polymer
5	B5	AC20-5TR	Asphalt cement with 2000 poises viscosity at 60°C, modified with 5% tire rubber

Environmental Conditions

The Texas environment was categorized into five climatic zones— Wet Warm (WW), Dry Cold (DC), Wet Cold (WC), Dry Warm (DW), and Moderate (M)—as shown in Figure 3. Each TxDOT district was differentiated by pavement surface temperatures at 50 and 98% reliability in TxDOT Project 0-1710. For SPG validation, only the temperatures at 98% reliability obtained from weather stations closest to the selected HSs were utilized. Table 7 shows the SPG grades that correspond to the five climatic zones. Only those binder-aggregate combinations typically used by TxDOT in surface treatments in these five environmental zones were considered for this study.

Table 7: Comparison of Required SPG Grade at 98% Reliability in Texas Environmental Zones

Zone	**Description**	**Required SPG Grade (98% Reliability)**
Dry Cold	Dry with freeze-thaw cycles	SPG 70-24, SPG 67-30
Dry Warm	Dry with no freeze-thaw cycles	SPG 70-18
Moderate	Moderate	SPG 67-24
Wet Warm	Wet with no freeze-thaw cycles	SPG 67-18
Wet Cold	Wet with freeze-thaw cycles	SPG 67-24

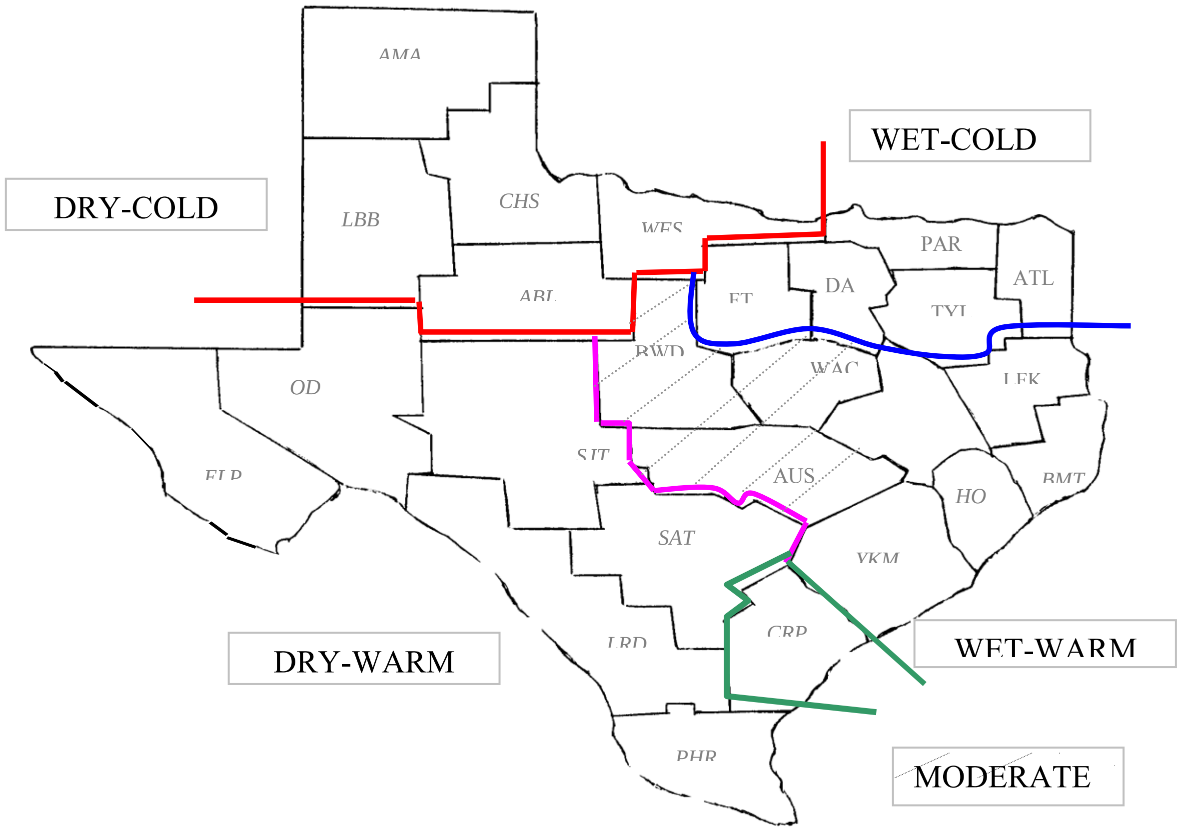


Figure 3: Climatic Zones in Texas

Aggregates

Seven commonly used aggregate types as described in Table 8—PB, PE, PL, SAC-A, SAC-B, E, and L (designated as A1 to A7, respectively)—were taken into account in the study. Six aggregate gradations, GR3 to GR7 and GR9, and five geological types, sandstone, limestone, gravel, lightweight, limestone rock asphalt (LRA), were also considered. Figure 4 and Figure 5 show TxDOT's typical gradation specifications for the most commonly used lightweight and non-lightweight aggregates (Walubita and Epps Martin 2005b).

Table 8: Aggregate Types

#	Designation	Aggregate	Brief Description
1	A1	PB	Precoated crushed gravel, crushed slag, crushed stone, or LRA
2	A2	PE	Precoated aggregate as shown on plans
3	A3	PL	Precoated lightweight aggregate
4	A4	SAC-A	High microtexture surface aggregate
5	A5	SAC-B	Moderate microtexture surface aggregate
6	A6	E	Aggregate as shown on plans
7	A7	L	Lightweight aggregate

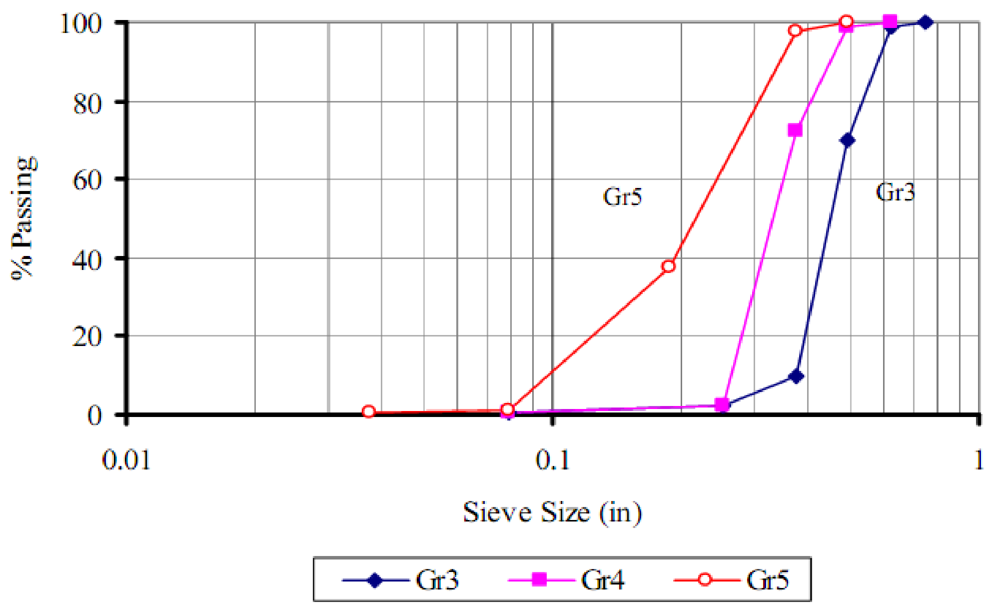


Figure 4: TxDOT Specified Gradation for Non-Lightweight Aggregates

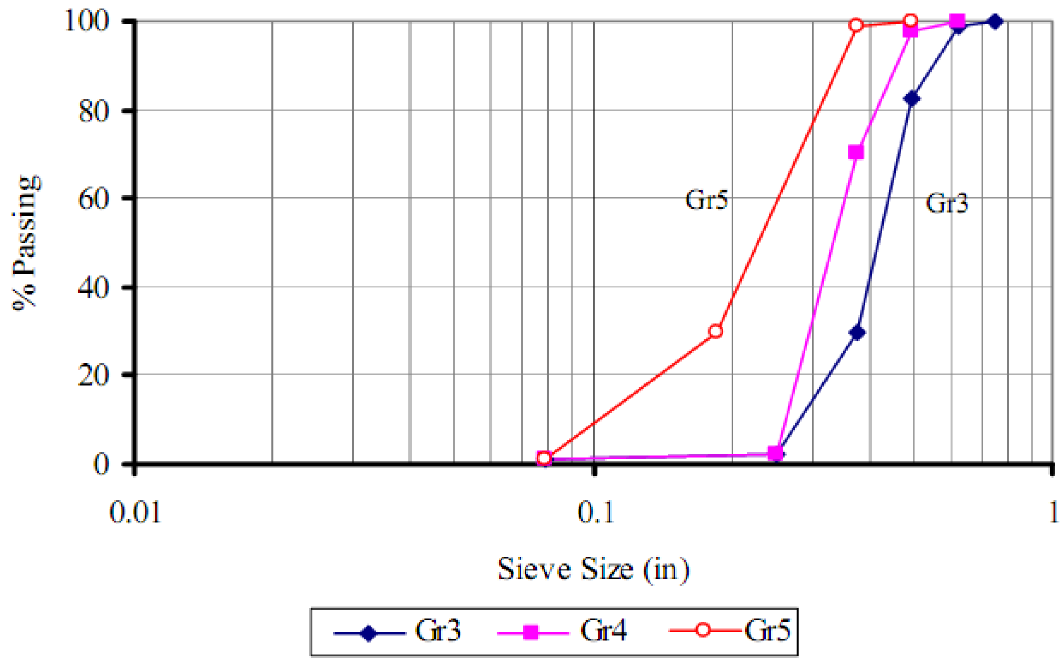


Figure 5: TxDOT Specified Gradation for Lightweight Aggregates

Traffic Volume

The traffic parameter considered in the experimental design was volume in terms of the annual average daily traffic (AADT). This is consistent with the TxDOT surface treatment design procedure in terms of the binder and aggregate application rates. AADT was categorized into three groups, high (T1), medium (T2), and low (T3). The threshold values for each group are shown in Table 9.

Table 9: Traffic Levels

Traffic Group	Thresholds
T1	AADT > 5000
T2	1000 ≤ AADT ≤ 5000
T3	AADT < 1000

Table 10 shows the HSs selected for monitoring with the corresponding project identification, county, highway, location (beginning and end Texas reference markers), section length, asphalt type, aggregate geologic type, and traffic level (traffic group denoted by shading).

Five districts, one in each one of the environmental zones, were selected: Atlanta (ATL), Brownwood (BWD), Childress (CHS), Lufkin (LFK), and San Antonio (SAT). With the exception of Childress, at least four sections were selected within each district, two with high traffic level, one with medium traffic level, and one with low traffic level. All sections in Childress corresponded to a low traffic level. Selections were made taking into account the reported condition of the existing pavement, trying to avoid as much as possible sections with excessive patching.

Field Performance Monitoring

Field sections selected from previous TxDOT Project 0-1710 and new field sections were surveyed using a visual survey technique, described subsequently, for monitoring the performance of surface treatments. Examples of a field performance monitoring survey sheet (Figure 6) and a distress evaluation sheet (shown in figure on Page 54) are provided subsequently in this section. The methodology used in this study is derived from techniques developed in TxDOT Project 0-1710 (Walubita and Epps Martin 2005b; Walubita et al. 2005a).

Table 10: Selected Sections

Zone	District	County	Hwy	HS ID	Begin RM	End RM	Distance (mi)	Asphalt	Aggregate	AADT 2011
Wet-Cold	Atlanta	CAMP	FM 2455	A-1	686+0.030	690+0.076	3.8	AC 20-5TR	Sandstone	410
		CAMP	FM 2254	A-2	696+1.500	700+0.337	2.8	AC 20-5TR	Sandstone	440
		TITUS	SH 11	A-3	724+0.000	730+0.000	4	AC 20-5TR	Sandstone	2867
		HARRISON	FM 968	A-4	710+0.000	712+0.787	2.9	AC 20-5TR	Sandstone	2000
		PANOLA	US 59	A-5	316+1.130	318+1.798	2.5	AC 20-5TR	Sandstone	7550
		UPSHUR	US 271	A-6	274+1.500	280+0.430	4.9	AC 20-5TR	Sandstone	7440
Moderate	Brown -wood	STEPHENS	FM3418	B-1	272-0.019	276+0.158	4.1	CRS-2	Limestone	270
		BROWN	FM0590	B-2	348+0.000	354+0.714	6.7	CRS-2	Limestone	327
		BROWN	US0377	B-3	438+0.310	444+0.091	5.8	CRS-2P	Limestone	2014
		COMANCHE	SH0016	B-4	350+1.894	354+1.5	3.6	CRS-2P	Limestone	2850
		COMANCHE	SH0016	B-5	354+1.5	356+1.123	1.6	CRS-2P	Limestone	5700
		BROWN	US0067	B-6	580+1.223	586+0.000	4.8	AC20-5TR	Limestone	5663
Dry-Cold	Childress	COLLINGSWORTH	FM 1035	C-1	127	130	2.1	AC10	Gravel	715
		KNOX	FM 2279	C-2	224	232	6.4	AC10	Gravel	160
		WHEELER	FM 2299	C-3	394	398	4.2	AC10	Gravel	70
Wet-Warm	Lufkin	SABINE	FM 1	L-1	460+0.001	462+0.000	2	CRS-2P	Lightweight	600
		SHELBY	SH 87	L-3	318+0.311	322+1.329	15.1	AC20-5TR	Lightweight	2582
		NACOGDOCHES	SH 21	L-4	784+1.500	788+0.227	2.7	AC20-5TR	Limestone	4400
		TRINITY	SH 19	L-6	414+1.876	420+0.000	3.3	AC20-5TR	Lightweight	5475
Wet-Cold	Paris	GRAYSON	FM 901	P-1	192	194+1.5	3.5	CRS-2P	Limestone	250
		RED RIVER	FM 3281	P-2	672	676+0.5	4.5	CRS-2P	Limestone	310
		GRAYSON	SH 91	P-3	194	196+1.0	3	AC 20-5TR	Limestone	3900
		HUNT	BU 69-D	P-4	236	238+0.5	2.5	AC 20-5TR	Limestone	2260
		GRAYSON	FM 1417	P-5	212	214	1.9	AC 20-5TR	Limestone	7100
		GRAYSON	SS 503	P-6	593	600	2	AC 20-5TR	Limestone	5881
Dry-Warm	San Antonio	MEDINA	FM 2676	S-2	460+0.000	466+0.000	5.6	AC15P	LRA	597
		WILSON	LP0181	S-3	518-0.158	520+1.698	3.7	AC15P	LRA	2514
		GUADALUPE	FM0725	S-4	488+1.906	496+1.076	7.3	AC15P	LRA	2993
		GUADALUPE	FM0078	S-5	514+0.045	524+0.363	10.3	AC15P	LRA	5571
		UVALDE	US0090	S-6	502-1.416	514+1.477	14.9	AC15P	LRA	7183

A visual survey is relatively easy and distinctively evaluates distresses directly related to surface binder properties to meet the objectives of this study. With visual examination, three performance-rating parameters (aggregate loss, bleeding, and overall) are provided and the distress failure mode can be defined easily. During these visual surveys, field measurements of distresses were recorded in square feet (ft^2) of affected surface area, consistent with the SHRP distress identification manual and the techniques developed in TxDOT Project 0-1710 ((Federal Highway Administration 2003; Walubita et al. 2005a)).

Results from the visual survey were utilized to determine the surface condition index (SCI) consistent with TxDOT Project 0-1710. This section provides additional detail on the definition of subsections, distresses to be examined, calculation of SCI for each field section, and SCI thresholds utilized in TxDOT Project 0-1710.

Test Section Selection

Consistent with the previous TxDOT Project 0-1710, a test section was defined as a representative subsection of a field section with an area of approximately 5000 to 7000 ft2 for which performance monitoring was conducted. Characteristics of a test section are as follows:

- Each test section was 500 ft long and 10 to 14 ft wide (equivalent highway lane width).
- Two to four test sections were established, depending on the length of the surface treatment project. Overall performance of the field section was taken as the average of the performance of the individual test sections.

FIELD INFORMATION COLLECTION SHEET

Project 417102/3
Superpave Binder Testing for Surface Treatment Binders

BINDER SAMPLE DETAILS		**District/County:**	*LUFKIN, Trinity*
SAMPLE LABEL:	*417102-02 (HS2)*	**Sample Date:**	*09/11/2001*
Size/Weight of Sample:	*1530 g*	**Sample Status:**	*Received (09/12/2001)*

HIGHWAY DETAILS			
Name of Highway/Road:	*US 287*	**Length of Section (km):**	*8.75*
Location:	*Groveton - From Victoria Street to Polk County line*	**Area/Section/ km Post:**	*8.75 miles eastwards*
Direction:	*Both lanes (eastbound and westbound)*	**Traffic Level:**	*Low*

CONTACT DETAILS			
Name of Firm:			*TxDOT - Lufkin District Office*
Contact Person: *W D (Maintenance Manager)*		Tel:	*936-635 3372*
		Email:	*jdn@dot.state.tx.us*

MATERIALS AND PAVEMENT DETAILS

Item		**Description**		
Seal Type (Single, Double or Triple)		*Single Seal*		
Binder	- Type:	*AC15 - 5TR*	Typical Design Application Rate (gal/sy):	*0.38*
	- Application Rate (gal/sy):	*0.42 (in wheel path)* *~0.45-0.46 (in middle)*	Binder Application Temperature (°C):	*177*
	- Breaking Time (min)	*N/A*	Pavement Temperature @ Time of Construction (°C):	*27*
	- Source/Supplier:	*BS1*		
Aggregate	- Type:	*Lightweight precoated with Koch CSS-1h*		
	- Size & Shape:	*Angular*		
	- Gradation:	*Grade 3*		
	- Application Rate (cy/sy):	*1/98*	Typical Design Application Rate (cy/sy):	*1/100*
	- Source/Supplier:	AS1		
Existing Pavement Structure/ Condition	- Surface/Thickness (inches):	*Limestone chip seal with hot-mix patches*		
	- Base/Subbase/Subgrade:	*Relatively in good condition except slick areas in wheelpaths*		
Date of Construction:		*09/11/2001 (09.00AM - 04.00PM)*	Traffic Control: *Pilot car and flag men*	
Rolling Compaction:		*5-6 pneumatic-tired rollers*		
Traffic Level (ADT):		*2750 (low volume, < 3000)*	Traffic Speed (mph):	*70*

WEATHER DURING CONSTRUCTION

					Special Conditions/Comments:
Weather: (Clear, Sunny, Cloudy, Rainy, Windy, Hazy, etc)		*Sunny*	Relative Humidity (%):	*46.70*	*1) Sample provided by Milton Liu from same tank as shipped to site.*
Temperature (°C)	- Highest:	*28.90*	Wind Direction and Speed (mph):	*NNE 8.00*	*2) Same sample/binder provided for FM1617*
	- Average:	*28.30*			*3) Binder received on 09/12/01*
	- Lowest:	*27.20*			
Rainfall/Snowfall (mm):		*0.06*			

Figure 6: Example Field Information Collection Sheet

- Multiple test sections were used for each field section to avoid the possibility of overrating or underrating performance due to the absence or presence of localized distresses or geometric features such as turns or changes in surface elevation.
- Data was collected from the outside lane only. This practice also increases safety. The survey was conducted from the shoulder or edge of the pavement. This was done to make traffic control easier.
- Intersections, junctions at access roads, grades, and curves were avoided to minimize the effects of extremely slow and turning traffic, which could exaggerate distress, and for safety reasons.
- Test sections were marked using existing reference points or objects such as road mile marker signs. New test sections were marked using reference spikes (cotton gin spindle) driven into the pavement at the start and stop of the field section, along with spray-painted markings. Global positioning system (GPS) coordinates and Texas Reference Markers (TRM) were also gathered and tabulated for each field section.

Distresses

Each test section was monitored for aggregate loss (raveling), bleeding, and cracking.

Aggregate Loss (Raveling)

Aggregate loss or raveling is the principal distress associated with surface treatments and controlled by the SPG specification system. Aggregate loss is the loss of loose materials (usually aggregate) that ravel from the surface or edges of the pavement.

The aggregate loss, in terms of square feet of affected surface area at each severity level, was recorded on a field performance monitoring survey sheet as shown in the example in Figure 7. Low, moderate, and high severity levels were identified, consistent with the SHRP distress identification manual as shown in Table 11.

Table 11: Severity Levels for Aggregate Loss

#	Level	Description
1	Low	The aggregate has begun to ravel off but has not significantly progressed. Evidence of loss of some fine aggregate.
2	Moderate	Surface texture becoming rough and pitted; loose particles generally exist; loss of fine and some coarse aggregates.
3	High	Surface texture very rough and pitted; loss of coarse aggregates.

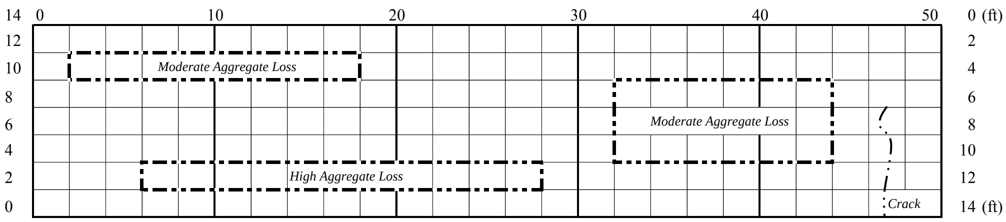
Bleeding

Bleeding occurs as a shiny, black, or glasslike reflective surface caused by liquid binder migrating to the pavement surface, often in the wheelpaths. It can also be defined as a film of excess bituminous binder occurring on the pavement surface. The result can be a dangerous, slippery pavement due to decreased frictional characteristics between the tire and pavement surface. Often, bleeding occurs at high pavement temperatures due to high binder content (associated with design and construction), low binder viscosity, use of very small aggregates and excessive embedment, inadequate and/or loss of aggregates, excessive compaction during construction, and high traffic.

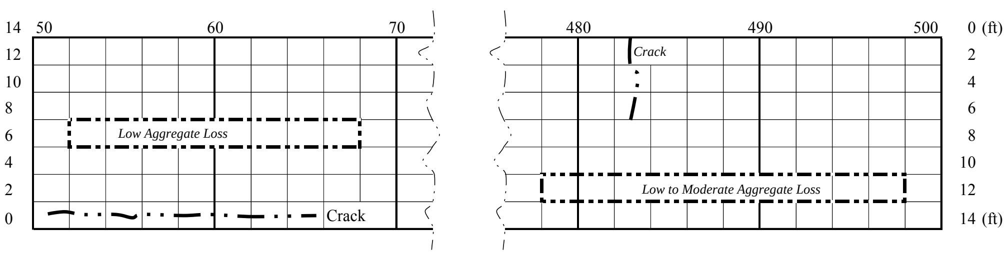
COMPLETED FIELD PERFORMANCE MONITORING SURVEY

VISUAL DISTRESS SURVEY SHEET

Hwy Section:	*HS P3*			Inspection No.	*3*
Date:	*9/5/2002*	Time:	*1.00PM*	Weather:	*Sunny*
Test Sction No.	1	Start:	*196 K6*	End:	*196 K6 + 500 miles*



Comment: *Aggregate embedment = approximately 65% in wheel path, and about 30 to 40 % between wheel path*



Comment: *Evidence of aggregate loss. Some transverse cracks from underlying structure. Generally - inadequate performance (aggregate loss)*

Surveyed by: *Tom Freeman*

Example of Distress Observations:
Consider for example, the following field survey observations on a particular highway section:

Aggregate Loss

Area coverage on 4 test sections:	***20%, 5%, 10%, and 3%***
Mean area coverage on 4 test sections:	***9.5%***
SCI score for distress area coverage (DAC):	***72%***
Severity levels for 4 test sections:	***Low to moderate, low to moderate, low, & low***
Percent severity on each test section is thus:	***10%10%, 5%, & 5%***
Mean percent severity:	***7.5%***
SCI score for degree of severity of aggregate loss (DSD):	***80%***

Cracking: ***Transverse cracking observed on some parts of the highway section***

Bleeding

Area coverage on 4 test sections:	***15%, 5%, 10%, & 10%***
Mean area coverage on 4 test sections:	***10%***
SCI score for distress area coverage (DAC):	***70%***
Severity levels for 4 test sections:	***High, low, moderate to high, & moderate to high***
Percent severity on each test section is thus:	***95%, 5%, 50%, & 50%***
Mean percent severity:	***50%***
SCI score for degree of severity of bleeding (DSD):	***300%***

Aggregate Embedment:	***60-90 % in wheel path***
	30-50 % between wheel path

Figure 7: Example Field Performance Monitoring Survey Sheet

Like aggregate loss, bleeding was defined and recorded in square feet of affected surface area at each of three severity levels (low, moderate, and high), consistent with the SHRP distress identification manual. The severity levels are described in Table 12.

Table 12: Severity Levels for Bleeding

#	Level	Description
1	Low	An area of pavement surface discolored (black) relative to the remainder of the pavement.
2	Moderate	Distinctive black appearance and loss of surface texture due to free excess binder.
3	High	Wet-black shiny appearance on the pavement surface due to excess binder; excess binder may obscure aggregates; tire marks may be evident in warm weather.

Cracking – Transverse and Longitudinal

Transverse (perpendicular to the pavement centerline) and longitudinal (parallel to the pavement centerline) cracks are not the primary focus in this study, but where observed, these distresses were recorded and reported in the analysis.

Performance Evaluation and Rating Criteria

The SCI criterion used in TxDOT Project 0-1710 for performance evaluation and rating of the sections were used in this study. The actual rating is based on calculated SCI scores, which range from 0.0% (very poor performance) to 100% (perfect performance). For each distress, the SCI score was calculated as an equal weighted function of the distress area coverage (DAC) and the degree of severity of distress (DSD), expressed as a percentage. This is illustrated in Equation 4.

$$\mathrm{SCI}_{\mathrm{Distress}} = 0.5(\mathrm{P}_{\mathrm{DAC}} + \mathrm{P}_{\mathrm{DSD}}) \qquad \text{Equation 4}$$

where:
$SCI_{Distress}$ = SCI score as a percentage for a given distress
P_{DAC} = distress area coverage as a percentage
P_{DSD} = degree of severity of a distress in percentage

The SCI scores for P_{DAC} and P_{DSD} were determined as shown in Figure 8 and Figure 9; a completed distress evaluation sheet is shown in Figure 10.

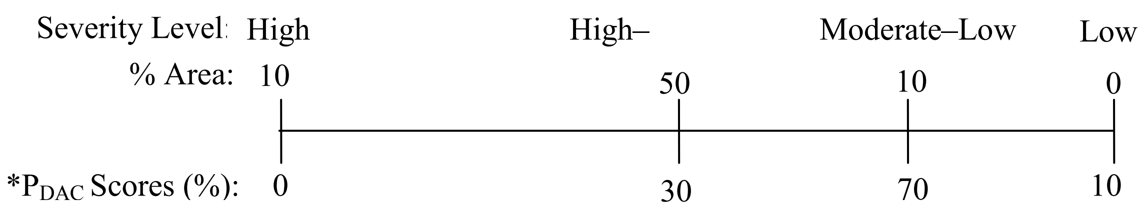


Figure 8: SCI Distress Evaluation and Scores – Distress Area Coverage (DAC)

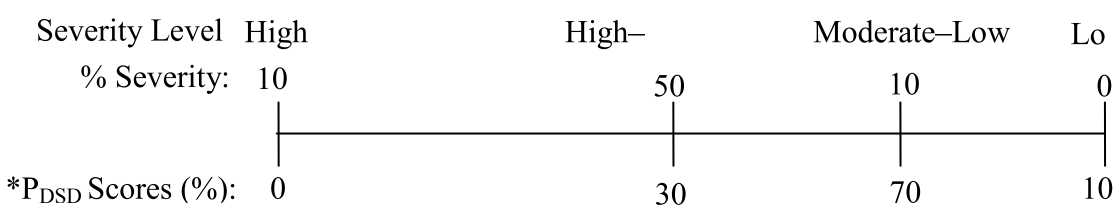


Figure 9: SCI Distress Evaluation and Scores – Degree of Severity of Distress (DSD)

Overall Field Section SCI Scores

For each field section, each distress was evaluated, analyzed, and reported separately, and then combined to get an overall field section SCI score and performance rating. This is illustrated in Equation 5 and Equation 6.

$$SCI_{Overall} = [\alpha_{AL} \times SCI_{AL}] + [\alpha_{BL} \times SCI_{BL}] + \cdots + [\alpha_{Distress} \times SCI_{Distress}] \quad \text{Equation 5}$$

and

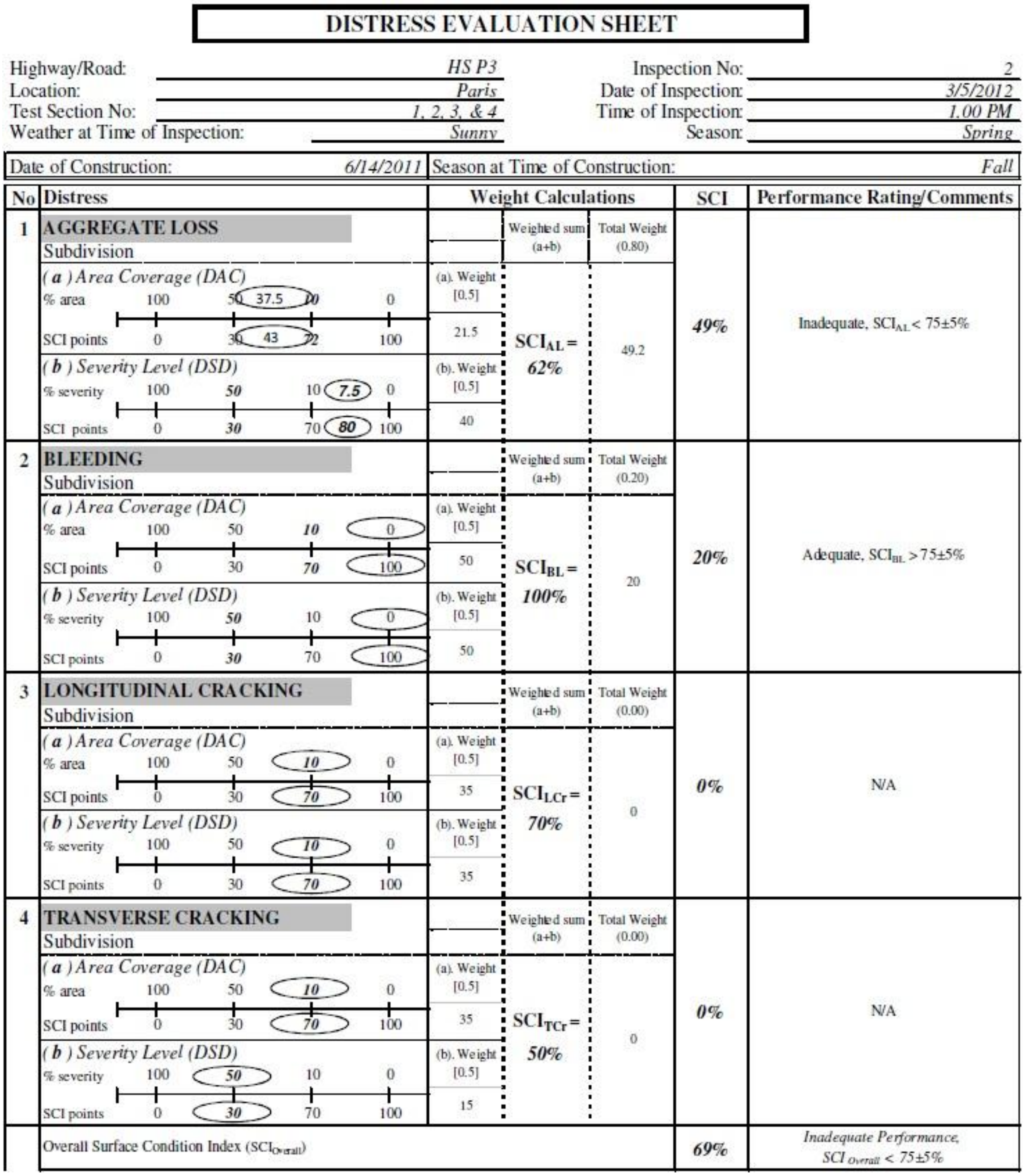
$$\alpha_{AL} + \alpha_{BL} + \cdots + \alpha_{Distress} = 1.00 \quad \text{Equation 6}$$

where:

$SCI_{Overall}$	=	overall field section SCI score as a percentage
SCI_{AL}	=	SCI score for aggregate loss as a percentage
SCI_{BL}	=	SCI score for bleeding as a percentage
$SCI_{Distress}$	=	SCI score for other distresses as a percentage
α_{AL}	=	distress weighting factor for aggregate loss (~0.80)
α_{BL}	=	distress weighting factor for bleeding (~0.20)
$\alpha_{Distress}$	=	distress weighting factors for other distresses

Table 13: Weighted SCI Scores by Distress Type

Distress	Weighting Factor (α_i)	Weighted Distress SCI Score (%) for Overall Field Section Performance
Aggregate Loss (SCI_{AL})	0.80	$0.80 \times (SCI_{AL})$
Bleeding (SCI_{BL})	0.20	$0.20 \times (SCI_{BL})$
Cracking (SCI_{Cr})	0.00	$0.00 \times (SCI_{Cr})$
Other Distresses ($SCI_{Distress}$)	0.00	$0.00 \times (SCI_{Distress})$
Total (assuming perfect performance)	1.00	100.00



DISTRESS EVALUATION SHEET

Highway/Road:	*HS P3*	Inspection No:	*2*
Location:	*Paris*	Date of Inspection:	*3/5/2012*
Test Section No:	*1, 2, 3, & 4*	Time of Inspection:	*1.00 PM*
Weather at Time of Inspection:	*Sunny*	Season:	*Spring*
Date of Construction:	*6/14/2011*	Season at Time of Construction:	*Fall*

No	Distress	Weight Calculations			SCI	Performance Rating/Comments
1	**AGGREGATE LOSS** Subdivision		Weighted sum (a+b)	Total Weight (0.80)	*49%*	Inadequate, $SCI_{AL} < 75\pm5\%$
	(a) Area Coverage (DAC) % area: 100, 50, 37.5, 10, 0; SCI points: 0, 30, 43, 72, 100	(a). Weight [0.5] 21.5	$SCI_{AL} =$ *62%*	49.2		
	(b) Severity Level (DSD) % severity: 100, 50, 10, 7.5, 0; SCI points: 0, 30, 70, 80, 100	(b). Weight [0.5] 40				
2	**BLEEDING** Subdivision		Weighted sum (a+b)	Total Weight (0.20)	*20%*	Adequate, $SCI_{BL} > 75\pm5\%$
	(a) Area Coverage (DAC) % area: 100, 50, 10, 0; SCI points: 0, 30, 70, 100	(a). Weight [0.5] 50	$SCI_{BL} =$ *100%*	20		
	(b) Severity Level (DSD) % severity: 100, 50, 10, 0; SCI points: 0, 30, 70, 100	(b). Weight [0.5] 50				
3	**LONGITUDINAL CRACKING** Subdivision		Weighted sum (a+b)	Total Weight (0.00)	*0%*	N/A
	(a) Area Coverage (DAC) % area: 100, 50, 10, 0; SCI points: 0, 30, 70, 100	(a). Weight [0.5] 35	$SCI_{LCr} =$ *70%*	0		
	(b) Severity Level (DSD) % severity: 100, 50, 10, 0; SCI points: 0, 30, 70, 100	(b). Weight [0.5] 35				
4	**TRANSVERSE CRACKING** Subdivision		Weighted sum (a+b)	Total Weight (0.00)	*0%*	N/A
	(a) Area Coverage (DAC) % area: 100, 50, 10, 0; SCI points: 0, 30, 70, 100	(a). Weight [0.5] 35	$SCI_{TCr} =$ *50%*	0		
	(b) Severity Level (DSD) % severity: 100, 50, 10, 0; SCI points: 0, 30, 70, 100	(b). Weight [0.5] 15				
	Overall Surface Condition Index ($SCI_{Overall}$)				*69%*	*Inadequate Performance, $SCI_{Overall} < 75\pm5\%$*

Figure 10: Example Distress Evaluation Sheet (Walubita and Epps Martin 2005b)

Table 14: SCI Threshold Values and Overall Performance Rating Criteria

SCI Threshold Value (Barcena et al. 2002; Epps Martin et al. 2001; Roque et al. 1991; Shuler 1990)	Performance Rating	SPG Validation
SCI $\geq$ 70%	*Good*	***SCI ≥ 70% = Pass (Adequate Performance)***
55% $\leq$ SCI < 70%	Fair	
SCI < 55%	Poor	***SCI < 70% = Fail (Inadequate Performance)***

Distress Weighting Factors and Threshold Values

The overall field section SCI score is the summation of the individual weighted distress SCI scores and should add up to 100% if performance is adequate with no distress. The weighted distress scores and SCI threshold values are summarized in Table 13 and Table 14, respectively. The distress weighting factors (α_i) of 0.80 for aggregate loss and 0.20 for bleeding were arbitrarily assigned based on the degree of significance of the distress in relation to surface treatment performance, the binder properties, and the SPG specification. Since only aggregate loss and bleeding were evaluated, weighting factors for other distresses such as cracking were zero (i.e., $\alpha_{Cr} \cong \alpha_{Distress} = 0.00$). During performance monitoring, surface treatment condition was recorded electronically using a digital camera.

Laboratory Testing

The primary objectives of this study are to revise the SPG specification by considering hot-applied asphalt cements and emulsions TxDOT commonly uses to evaluate two emulsion residue recovery methods, explore the exclusive use of the DSR for determining performance-based properties, and further field validate binder properties that control surface treatment performance in service.

Table 15: Test Plan

Test		**Conditions**	**Result Recorded**
Residue Recovery	Forced Draft Oven	60 g; 24 h at 25°C and 24 h at 60°C	Amount Residue Recovered
	Texas Oven	0.015"; 6 h at 60°C	
Water Removal and Oxidation	*GPC*		Peak at a time of 35 to 37.5 min in chromatogram
	FTIR		Carbonyl area
	ASTM D95		% solids
DSR High Temp	*Dynamic Shear*	High temp; 10 rad/s	G*/Sin δ
	MSCR	High temp High temp at 3.2 kPa	J_{nr}, J_{nr} ratio % recoverable strain
	Shear Strain Sweep	25°C; 10 rad/s linear loading from 1-50% strain, 1 sec time delay & 20-30 increments	Percent strain at 0.8G*
PAV @ 100°C			
DSR	*Shear Strain Sweep*	25°C; 10 rad/s linear loading, 1% strain, 1 sec time delay	G_i*
	MSCR	High temp at 3.2 kPa	Recoverable strain ratio
	Frequency Sweep	5°C, 10°C, 15°C; 0.1-20 Hz; 1% strain, 10 s time delay	
BBR	*Low-temp creep stiffness*	Low temp; 8s	S and m-values

In order to meet these objectives, an array of emulsion residue recovery, chemical tests, rheological tests, and SPG grading were performed on samples of binders used during the application of surface treatments for the selected HSs. The binders were sampled onsite during construction. Table 15 shows the details of the laboratory evaluation carried out as part of this study. Those tests that appear in italics were also performed as part of TxDOT Project 0-1710 and NCHRP Project 14-17 using similar testing conditions.

Residue Recovery Methods

Two emulsion residue recovery methods were used in this study to extract the water from the emulsions and to supply de-watered emulsion residue for material properties testing. The residue recovery methods employed were (a) Force Draft Oven and (b) Texas Oven methods.

The Force Draft Oven method follows the Method A procedure in ASTM D7497-09. The emulsion was poured into a 9-in^2 silicone mold and spread evenly with a spatula to give a spread rate of 1.5 to 2.0 kg/m^2 of emulsion. The silicone mat was then be placed into a 25 ºC forced draft oven. After 24 h, the silicone mat was transferred to a 60 ºC forced draft oven for another 24 h. Then, the mat was allowed to cool for one hour at room temperature prior to emulsion residue removal. The recovered emulsion residue was then removed from the mat using a plastic utensil and kneaded into the appropriate sample size for chemical or rheological testing. This procedure does not involve any stirring or agitation of the emulsion residue during recovery, and the total recovery time is approximately 48 hours.

The Texas Oven method follows the Method B proposed procedure in ASTM D7497-09. The emulsion was poured onto a silicone mat and in one continuous motion spread evenly with a wet film applicator to obtain a wet film thickness of 0.381 mm. The silicone mat was then placed in a 60 ºC forced draft oven for 6 h. The mat was allowed to cool for 15 minutes at room temperature prior to emulsion residue removal. The recovered emulsion residue was removed from the mat by peeling using a uniform rolling motion with a metal rod. The recovered residue was then shaped appropriately for chemical or rheological testing. This procedure also does not employ any stirring or agitation of the emulsion residue during recovery, and the total recovery time is approximately 6 h.

Aging

All tests used for the determination of the ageing effects and water removal efficiency of the residue recovery methods were performed by the researchers at the Artie McFerrin Department of Chemical Engineering. GPC was performed on each recovered residue to assess the completeness of water removal by the emulsion residue recovery process. GPC is a size exclusion chromatography (SEC) method of molecular analysis. The presence or absence of a peak on the GPC chromatogram indicates the presence or absence of water in the residue, respectively. The method is very sensitive to the presence of water, as are the rheological properties of the emulsion residues.

FTIR spectroscopy was performed on the emulsion residues to assess the extent of any oxidation that occurred during the emulsion residue recovery processes. Differences in the carbonyl area for the same emulsion residue but recovered by different methods is used to indicate differences in oxidation by the different emulsion residue recovery methods (Epps Martin et al. 2001; Mitchell et al. 2010). Further, this carbonyl area can be compared to that of the base binder, if available, to determine if the emulsifying process and emulsion residue recovery method cause oxidation. As an example of FT-IR analyses, (Mitchell et al. 2010) found that the Force Draft Oven method, which exposes the binder residue to atmospheric air during the recovery process, produced emulsion residue with statistically higher viscosity and carbonyl area values than the original base binders, suggesting some oxidative hardening by the Force Draft Oven method. This oxidation could have occurred during emulsification or during the emulsion residue recovery process. The hot oven and stirred can methods, which use a nitrogen environment for the recovery, do not appear to produce a statistically significant increase in oxidative hardening.

Exclusive Use of DSR for Characterizing Surface Binders

In the existing SPG specification, the BBR test is the only rheological test not performed using the DSR. As part of this study, an alternative to the BBR test was sought for characterizing the low-temperature properties of surface binders. The possibility of predicting the BBR test parameters—creep stiffness and m-value—from parameters measured using the DSR frequency sweep test was explored.

The criteria for the low-temperature properties of the binders included in the SPG specification were developed to ensure the selection of binders resistant to aggregate loss at low temperatures. The SPG specification prescribes a modified BBR test, wherein the flexural creep stiffness (S) and the log stiffness-log time slope (m-value) are measured at the low-temperature limit and a loading duration of 8 s for PAV-aged binders. The BBR test requires about 15.5 g of material in the form of a beam specimen that is 5-in long by 0.5-in wide by 0.25-in thick. The test was repeated at 3°C decrements until the lowest temperature is reached at which the creep stiffness (S) value is more than 500 MPa and the m-value was at least 0.24, as per the existing SPG guidelines for laboratory failure at low temperatures (AI 2003; Epps Martin et al. 2001). The binder samples tested using the BBR were PAV aged for 20 h at 2.1 MPa pressure and 90°C temperature (AI 2003). The low-temperature limit of the SPG grade was obtained from the BBR results and represents the 1-day minimum pavement surface design temperature.

The frequency sweep test in the DSR was performed to obtain the complex modulus and phase angle values from which the BBR parameters, S and m-value, were predicted. Subsequently, the predicted and measured values of S and m-value were compared to ascertain the fit of the prediction model. Frequency sweeps were performed on PAV-aged binder samples with 8 mm plates and a 2 mm gap in the DSR at frequencies ranging from 1 to 150 rad/s (~0.15 to 23.9 Hz) and intermediate temperatures of 15 ºC, 10 ºC, and 6 ºC. (The lowest stable temperature that could be obtained on the DSR machine used in this study was 6°C.) The frequency sweep test requires about one-fifth the amount of material required in the BBR test. The appropriate frequency for testing that enables the comparison of the DSR parameters with the BBR parameters was determined using Equation 1 (Anderson 1994; Hanz and Bahia 2010). Estimates of S and m at 8 s and 60 s loading times, obtained from the complex modulus G^* and phase angle δ using Equations 2 and 3, were compared to actual BBR measurements (Anderson 1994).

The development of these relationships is expected to eliminate the need for BBR testing in future specifications for surface binders.

Existing SPG Tests

The binder characterization tests specified in the modified SPG system, shown in Table 2, were carried out using the same equipment and criteria. For each test, three replicate specimens were tested.

Basic DSR Test

A Malvern/Bohlin DSR-II with 25 mm plates and 1 mm gap was used for high-temperature binder testing and SPG grading. In this test, the complex shear modulus G^* and phase angle δ of unaged emulsion residue and base binders are measured at temperature grade increments of 3°C to obtain the highest temperature at which $G^*/\sin\delta$ is at least 0.65. These high-temperature properties are important to ensure aggregate retention and to prevent bleeding in surface binders at high temperatures. DSR testing provides the upper limit of the binder grade; this high-temperature limit represents the average 7-day maximum pavement surface design temperature.

Strain Sweep

DSR strain sweep testing at an intermediate temperature of 25˚C was performed to assess the strain susceptibility and resistance to raveling of both unaged and PAV-aged emulsion residues and base binders. In the strain sweep test, the material response to increasing deformation amplitude is monitored at a constant frequency and temperature. Strain sweep testing was used in this study to evaluate the resilience and strain tolerance of emulsion residues or their ability to retain aggregate and resist raveling. Strain sweep testing was conducted on the standard DSR with 8 mm plates and a 2 mm gap. The test was performed at a temperature of 25°C on the basis of typical surface treatment construction temperatures and previous research (Hanz and Bahia 2010; Hoyt et al. 2010; Kucharek 2007). A thermal equilibrium time of 10 minutes was allowed after mounting the sample and before testing began. In the standard immersion cell that is part of the DSR, the sample and both upper and lower plates are immersed in the temperature-controlling fluid; this enables close temperature control, with temperature gradients of <0.1ºC through the sample. The loading frequency used in the test was 10 rad/s (1.59 Hz) as specified by the Superpave system. Twenty measurements were recorded at various strain levels ranging from 1 to 50%. This range was selected to capture the full range of strain levels that most binders tested in this study can resist. A delay time of 1 s was applied after the application of each strain level, but before the measurements were recorded, to allow the sample to attain equilibrium at the strain level. In cases where the DSR was incapable of reaching a 50% strain level (due to insufficient torque when testing stiffer materials), all measurements after the maximum stress was reached were recorded at or very near that maximum stress point.

New Rheological Tests

MSCR Test

In this study, the MSCR test was used to characterize the resistance of the emulsion residues and hot-applied binders to bleeding. This test simulates loading caused by the repeated passage of traffic over a spot on the pavement. The test was performed on unaged material to determine the elastic response of the binders under shear creep and recovery at two stress levels. The test temperature was the upper temperature of the binder grade as determined through high-temperature testing using the DSR. The MSCR test was performed on the same equipment (a Malvern/Bohlin DSR-II) and using the same configuration and sample size (with 25 mm plates and 1 mm gap) as in the high-temperature DSR test. The samples were loaded at constant stress for 1 s then allowed to recover for 9 s. Ten creep and recovery cycles were run at a creep stress of 100 Pa followed by ten at a creep stress of 3200 Pa. The strain accumulated at the end of the creep and recovery portions was recorded and used to estimate the average percent recovery and the non-recoverable creep compliance (J_{nr}) of the binder. J_{nr} is the ratio of the maximum accumulated strain at the end of the test to the maximum stress level applied to the binder. The MSCR test was utilized to identify the elastic response of the binders and the change in the elastic response at the two stress levels. The percent recovery of binders determined in this test is dependent on the extent of modification of the binder and can be used to determine if modified binders offer a better elastomeric response. J_{nr} is an indicator of the binder's resistance to bleeding under repeated loading.

Percent recovery, ε_r (100,N) for N = 1 to 10 is obtained from Equation 7:

$$\varepsilon_r(100, N) = \frac{\varepsilon_{10} - \varepsilon_1}{\varepsilon_1} \times 100 \qquad \text{Equation 7}$$

where ε_{10} is the adjusted strain value at the end of recovery portion of each cycle and ε_1 is the adjusted strain value at the end of creep portion of each cycle.

Further, the non-recoverable compliance J_{nr} (σ, N) for N = 1 to 10 is obtained from Equation 8:

$$J_{nr}(\sigma, N) = \frac{\varepsilon_{10}}{\sigma} \qquad \text{Equation 8}$$

where ε_{10} is the adjusted strain value at the end of recovery portion of each cycle and σ is the applied stress.

Summary

This chapter presented the wide variety of test methods employed to meet the objectives of this study. Several test methods were used for the recovery, evaluation, and characterization of emulsion residues and hot-applied surface treatment binders. The details and parameters of these laboratory tests were described. Further, the methods and factors using which the HSs were selected were discussed in detail. Moreover, the procedure for calculating the SCI scores for the selected HSs was defined. The results obtained using these methods are detailed and analyzed in Chapter IV.

CHAPTER IV

RESULTS AND ANALYSIS

The results of the laboratory testing and field performance monitoring activities conducted in this study are discussed in this chapter. Further, the laboratory and SCI field performance results are summarized in Appendices A and B. Digital images of the selected HSs and the distresses observed in the field have been used to illustrate the discussion.

Laboratory Test Results

Four types of laboratory tests (the basic DSR, strain sweep, frequency sweep, and BBR tests) were performed on the emulsion residues and hot-applied binders collected from the highway sections (HSs) in this study. Of these, three tests (the basic DSR, strain sweep, and BBR tests) were used to grade the binders tested according to the existing SPG specification. The detailed results of all the tests performed in this study are presented in this section.

Residue Recovery

Two residue recovery methods were employed to obtain emulsion residues in this study. These two methods were evaluated in terms of water removal efficiency and oxidative aging using the GPC and the FTIR. The results of the evaluation are shown in Appendix A. The GPC chromatograms from the residues, shown in Figure 11, obtained from both recovery methods indicated the presence of some water in the recovered emulsion residues, indicating that water had not been completely removed from the emulsions during the recovery procedures.

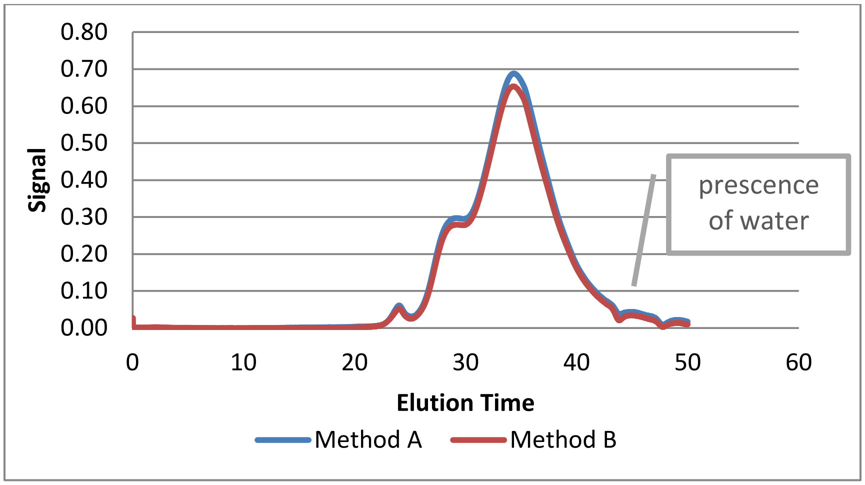


Figure 11: GPC Results for Binder Residues (Section B-3)

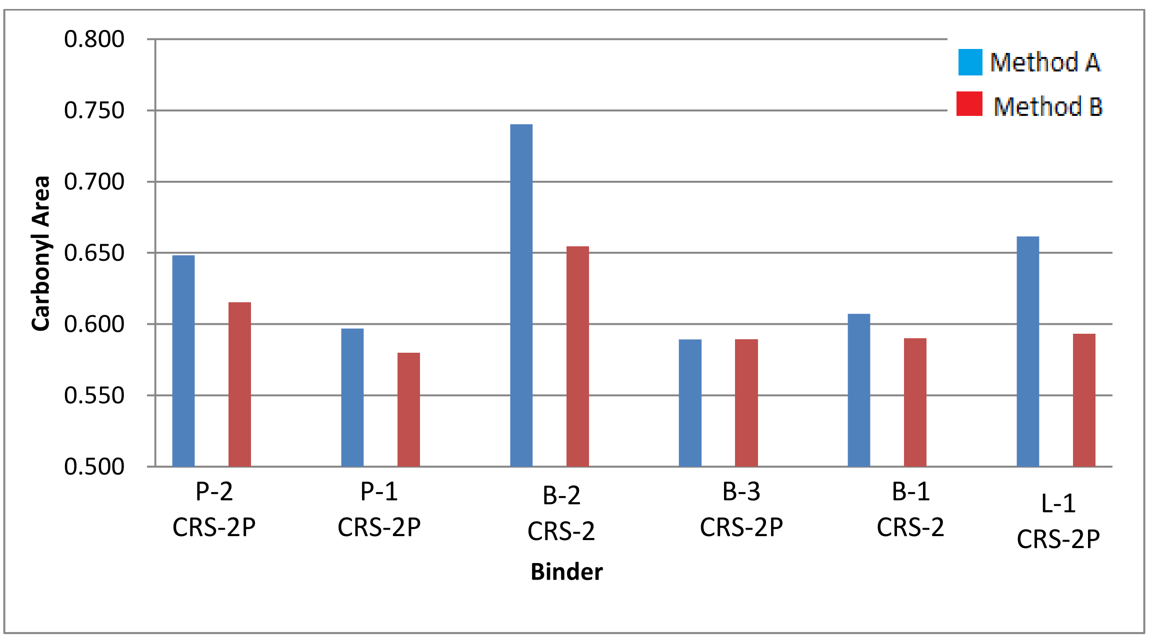


Figure 12: Carbonyl Area Comparisons for Recovery Methods

Further, the carbonyl areas calculated from FT-IR spectra for the emulsions indicated that the residues recovered from Method A were more oxidized than residues obtained from Method B (Figure 12). Moreover, the binder residue from Method A appeared visibly stiffer than that from Method B. Moreover, Method A sometimes resulted in residue that retained more stiffness at higher temperature than residue from Method B, as shown in Figure 13.

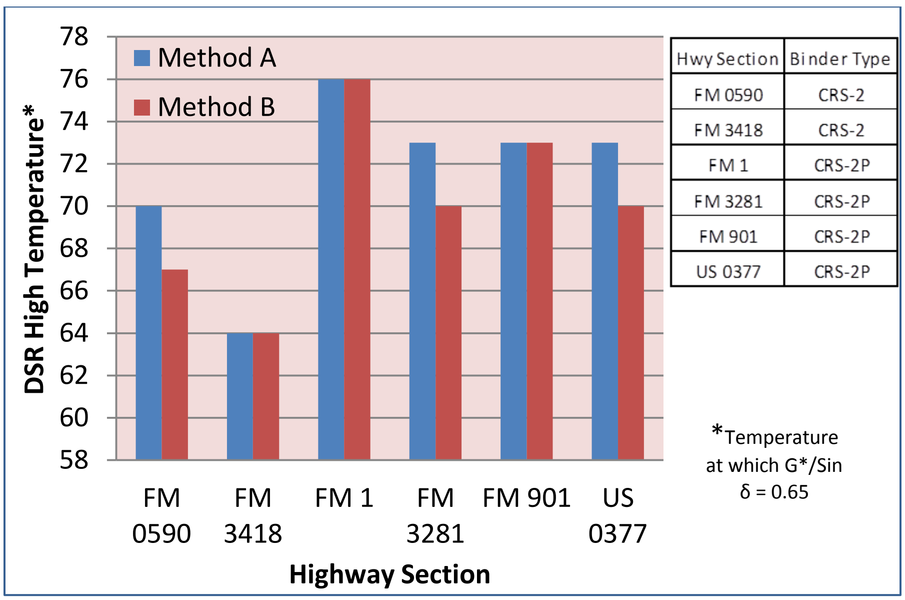


Figure 13: DSR High Temperature Comparison for Method A and Method B Residues

The strain tolerance (from strain sweep test) and non-recoverable creep compliance (from MSCR test) values for residues obtained from the two methods were found to be statistically similar. Based on these results, residue from Method B was concluded to be closer to the residue obtained in the field. Furthermore, Method B (6 h) is shorter than Method A (48 h) and may be more practical for recovering large quantities of emulsion residue. The SPG grading results reported for all the emulsions in this study are based on the results obtained for residues from Method B.

Strain Sweep Test Results

The strain sweep test, which was part of the modified SPG specification (Hoyt et al. 2010), was conducted on unaged and aged binder residues and hot-applied binders in this study. The binder properties associated with aggregate retention (resistance to raveling) can be quantified in terms of the percentage drop in modulus or strength with increasing strain at a constant temperature and frequency. As can be seen in Figure 14, the modulus remains constant as strain increases until at some critical strain level it drops significantly. The complex modulus G* is constant in the linear region; a 10% drop in G* indicates that the material has begun to behave non-linearly and is accumulating strain. Further, it has been found that a 50% reduction in G* is akin to failure (Hanz et al. 2009).

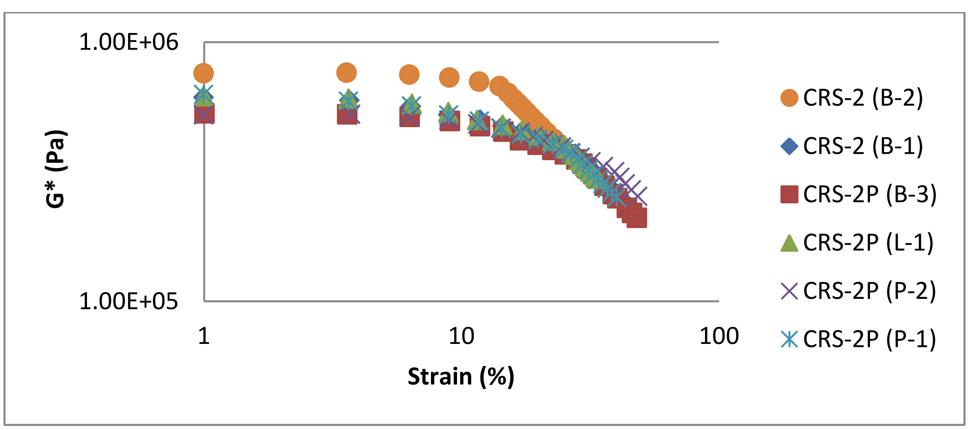


Figure 14: Strain Sweep for Unaged Emulsion Residues

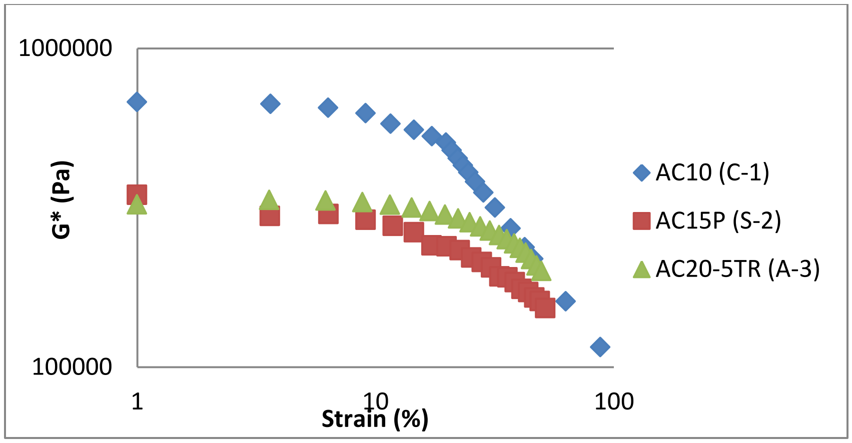


Figure 15: Strain Sweep for Unaged Hot-Applied Binders

As can be seen in Figure 14 and Figure 15, modified binders were found to have better strain tolerance as indicated by higher (significant differences at a level of significance of 0.05 in a two-tailed t test) strain at failure (50% reduction in G*) than unmodified binders.

This test was used to assess whether the binder develops adequate strain tolerance and stiffness to prevent the bond between the aggregate and the binder from failing. The modified SPG recommends a minimum percent strain of 25 at $0.8G_i$* for unaged binders and a maximum G_i* of 2.5 MPa for PAV-aged binders (Table 2). Of the 30 unaged binders tested, 13 binders fail the minimum strain criterion (i.e., have percent strain less than 25%). These 13 binders can be expected to have low strain tolerance and insufficient resistance to raveling in the field according to the modified SPG specification. Further, three binders had invalid strain sweep results (i.e., the maximum DSR stress was reached before the modulus G_i* could decrease by 20%). For all 30 binders, either the maximum DSR stress was reached or the test itself ended (entire strain range was completed) before a 50% decrease in G_i* was observed. Moreover, none of the PAV-aged binder samples fail the criterion prescribed for aged binders in the modified SPG specification (maximum G_i*_{aged} of 2.5 MPa. The PAV-aged binders lose their ability to resist the strain sooner than unaged binders, as shown in Figure 16. This is expected as unaged binders with lower stiffness would be more capable of resisting shear loads at high strains than PAV-aged binders.

The results of the strain sweep test are summarized in Appendix A. It should be noted that the strain sweep criteria in the modified SPG specification were based on a limited dataset. Based on the field performance of the binders tested in this study, these strain sweep limits were revised as discussed subsequently to better reflect the correlation between laboratory and field results.

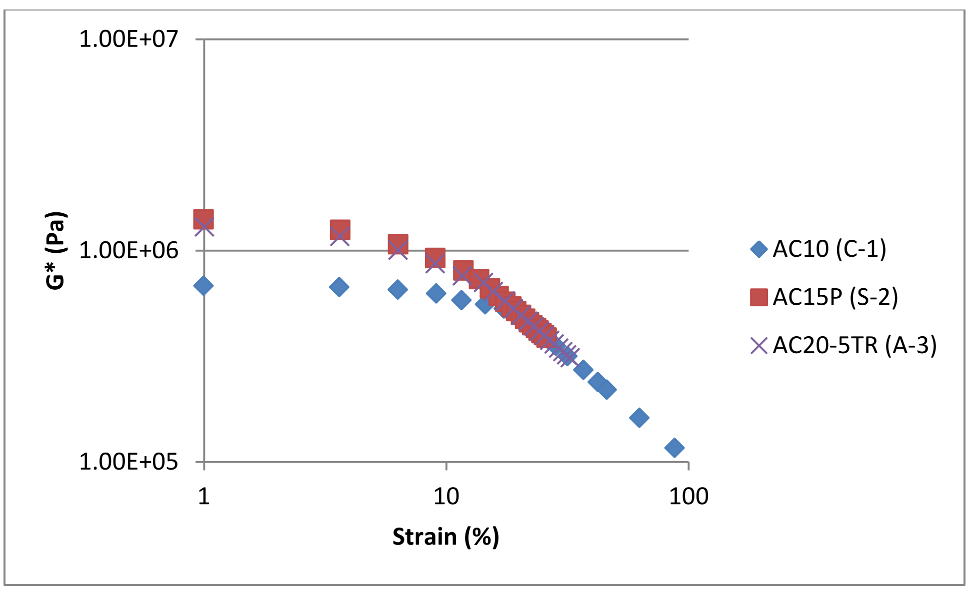


Figure 16: Strain Sweep for Aged Hot-Applied Binders

MSCR Test Results

The MSCR test specified in AASHTO TP70 was conducted on unaged binders and emulsion residues to identify the elastic response and the change in the elastic response at two stress levels, 100 Pa and 3200 Pa (AASHTO 2010). The parameters measured in the MSCR tests—the non-recoverable creep compliance (J_{nr}; the residual strain in the specimen after a creep and recovery cycle, relative to the amount of stress applied) and the percent recovery (the extent to which the sample returns to its previous shape after being repeatedly stressed and relaxed)—indicate the binders' resistance to flow and bleeding.

There were no significant differences (using a two-tailed *t*-test at the 0.05 level of significance) between the J_{nr} and the percent recovery for residues obtained by the two recovery methods. Further, as shown in Figure 17, the percent recovery exhibited by the modified binders was significantly greater than that of the unmodified binders at the test temperatures. Additionally, the non-recoverable creep compliance for all the modified binders was lower than that of the unmodified binders (Figure 18). The differences between the J_{nr} and percent recovery values for modified and unmodified binders were found to be statistically significant ($p<0.05$).

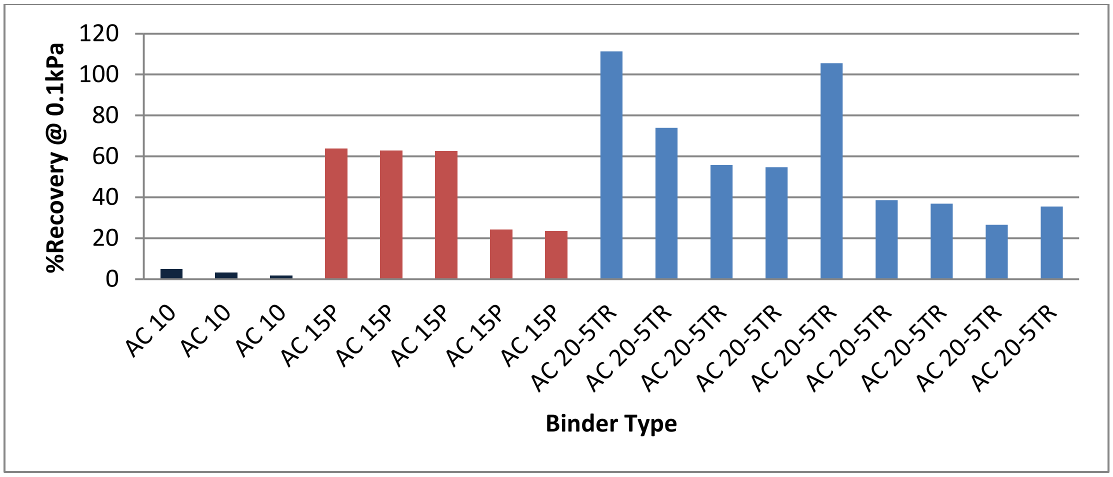


Figure 17: Percent Recovery for Hot-Applied Binders

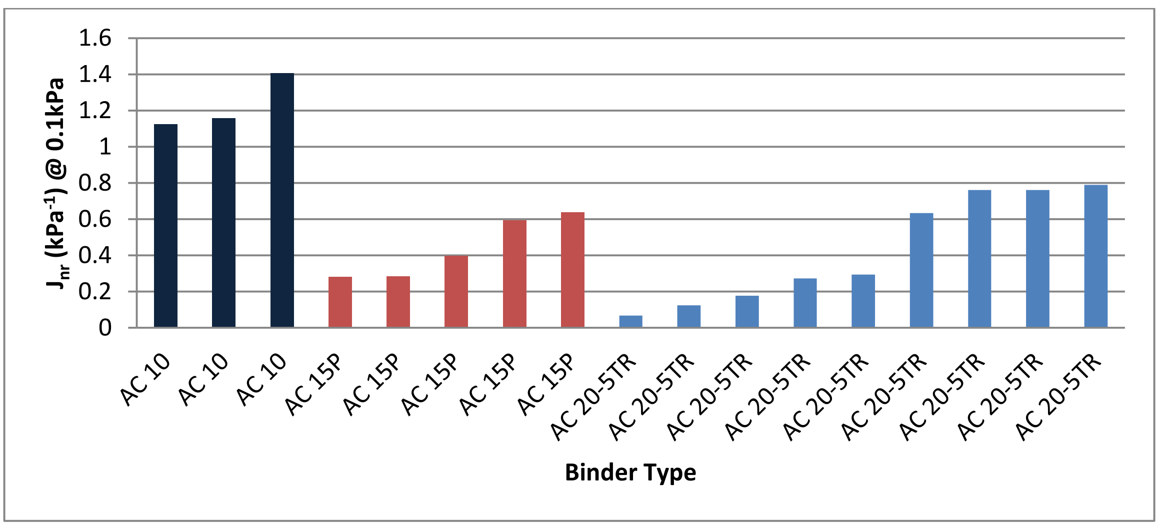


Figure 18: J_{nr} at 0.1 kPa for Hot-Applied Binders

Some of the unmodified AC10 binders have J_{nr} values that are two to five times larger than those of the modified AC15P and AC20-5TR binders. It has been suggested that the doubling of the J_{nr} value is equivalent to softening by one binder grade (King et al. 2010). This implies that these unmodified binders would receive binder grades much lower than the modified binders. AC10 binders were indeed graded lower (up to three grades lower) than the AC15P and AC20-5TR binders based on the DSR high temperature criteria. However, by the same rule, the AC20-5TR binder from HS B-5 should be at least one binder grade lower than the AC20-5TR binder from HS B-6 and other AC20-5TR binders. The grading results reveal that this is not true and shows a lack of correlation between the DSR high and MSCR results.

Further, while the J_{nr} values for all binders increase with an increase in the stress level, the performance of samples belonging to the same binder type at the two stress levels was found to be inconsistent, as can be seen in Figure 19. For example, the AC20-5TR binders from HS B-4 and B-5 have among the lowest J_{nr} values (0.21 kPa^{-1} and 0.29 kPa^{-1}, respectively) at 0.1 kPa but exhibit very high J_{nr} values (2.77 kPa^{-1} and 0.29 kPa^{-1}, respectively) at the 3.2 kPa stress level. This is also reflected in the recovery values recorded for these binders, which were very high at the lower stress level and at less than 5% at the higher stress level. This has been explained by the disentanglement of polymer chains in modified binders in previous studies (D'Angelo 2010). For some binders, the increase in stress level caused the percent recovery values to reduce to values less than zero indicating lack of elasticity at high stress levels. This phenomenon was observed mostly among the unmodified CRS-2 and AC10 binders, but was also seen in one CRS-2P binder (HS B-3). Most of the unmodified binders had varying percent recovery values at 3.2 kPa ranging from 0.23% to around 50%. This difference in performance can be attributed to the superior polymer networks in the modified binders. Therefore, the percent recovery parameter can be used to identify the presence of elastomers.

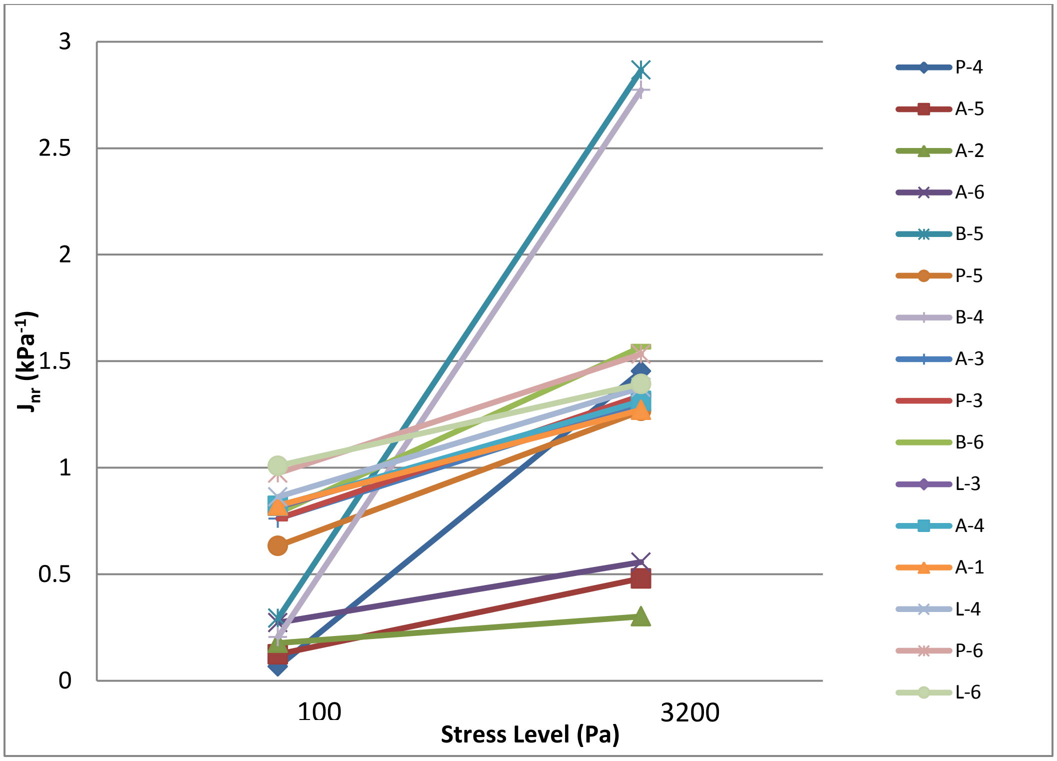


Figure 19: J_{nr} at 0.1 and 3.2 kPa for AC20-5TR binders

Since the percent recovery reflects the elastic response of the materials, the MSCR results indicate that binders classified as AC15P, AC 20-TR, and CRS-2P among those tested will exhibit the best elastic response. All the materials tested in this project can be expected to perform well in terms of bleeding based on the limits for J_{nr} (maximum value of 4 for standard traffic loads) proposed in newly developed HMA binder grading protocols (D'Angelo 2010). These limits, however, need to be revised through field validation to be suitable for surface treatment binders.

Frequency Sweep Test Results

Frequency sweeps specified in AASHTO T315 (AASHTO 2008) were performed on PAV-aged binder samples in the DSR at frequencies ranging from about

0.01 Hz to 23.9 Hz and intermediate temperatures of 15ºC, 10ºC, and 6ºC (The low-temperature capabilities of the DSR used did not allow reliable measurements below 6ºC). The complex modulus G* and phase angle δ obtained at these intermediate temperatures and frequencies were used to estimate the stiffness parameters (S and m-value) at -16ºC and -19ºC and 8 s and 60 s loading times using Equations 1, 2, and 3 proposed in SHRP Report A-369 (Anderson). These estimated S and m-values were compared with values obtained from BBR testing as shown in Figure 20-23.

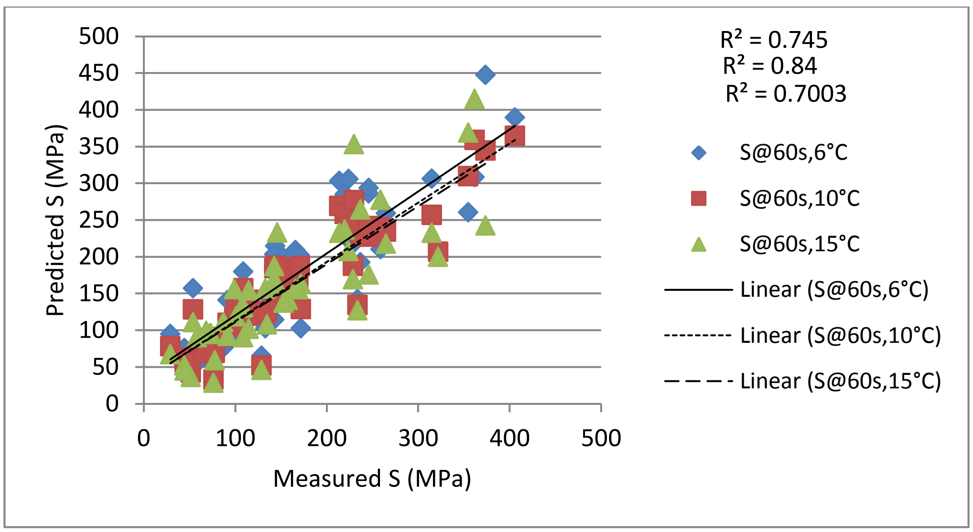


Figure 20: Comparison of Measured (BBR) S and Predicted (Frequency Sweep) S @ 60 s Loading Time

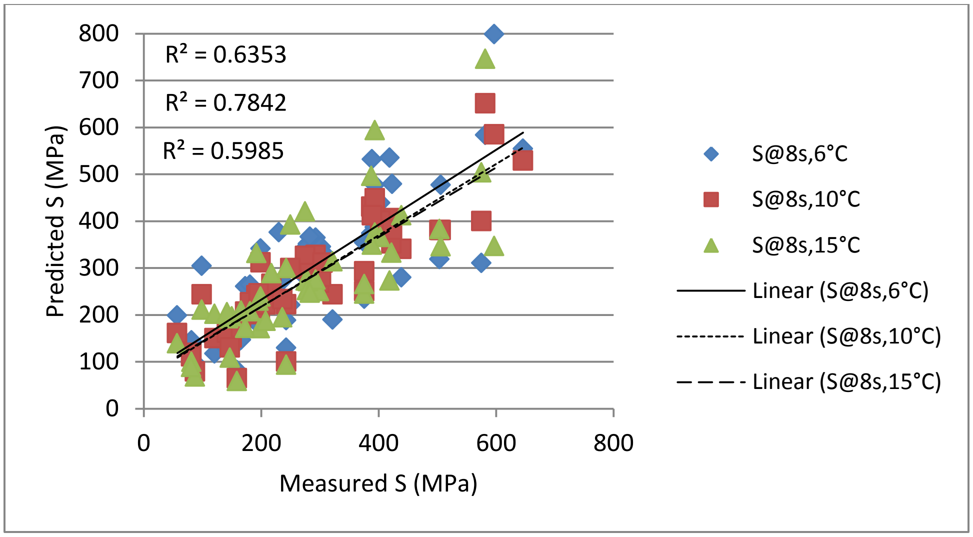


Figure 21: Comparison of Measured (BBR) S and Predicted (Frequency Sweep) S @ 8 s Loading Time

The DSR used in this study was capable of applying only a limited range of frequencies for which it is not possible to predict the BBR parameters directly at the low temperatures used in this study. However, it was possible to extrapolate the G* and δ values using the available DSR frequency sweep test results and, in turn, the BBR S and m-value in order to compare with the measured BBR data. This method may not be suitable for accurately modeling BBR results for loading times of less than 60 s. This is evidenced in the poor correlation between the compared S values for 8 s loading time (Figure 21). Further, the correlation between the predicted and measured m-values at both 8 s and 60 s loading times was much weaker than in the case of the creep stiffness values (Figure 22 and Figure 23). This could also be a result of the unreliability of the predictive equations at the very low BBR temperatures used in this study.

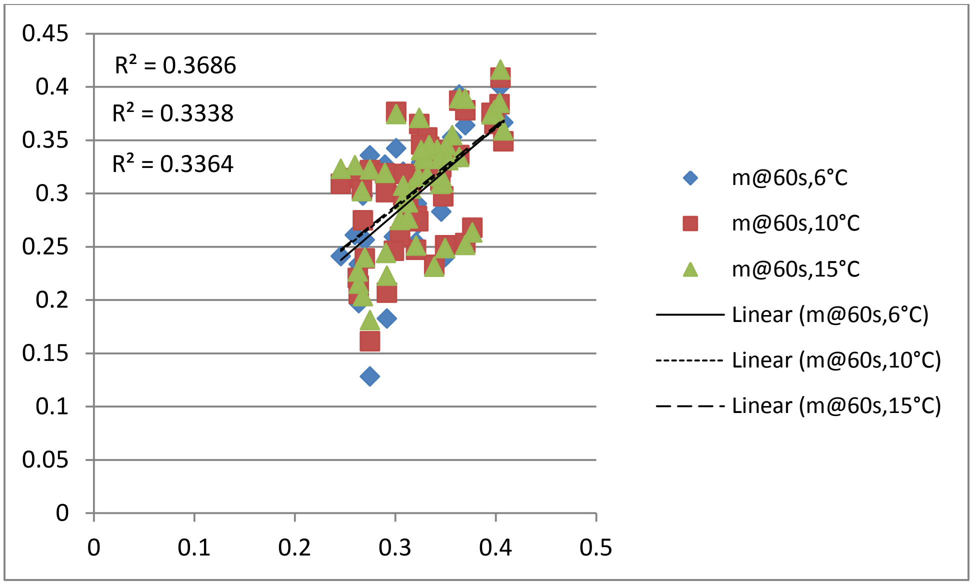


Figure 22: Comparison of Measured (BBR) and Predicted (Frequency Sweep) m-values at 60 s Loading Time

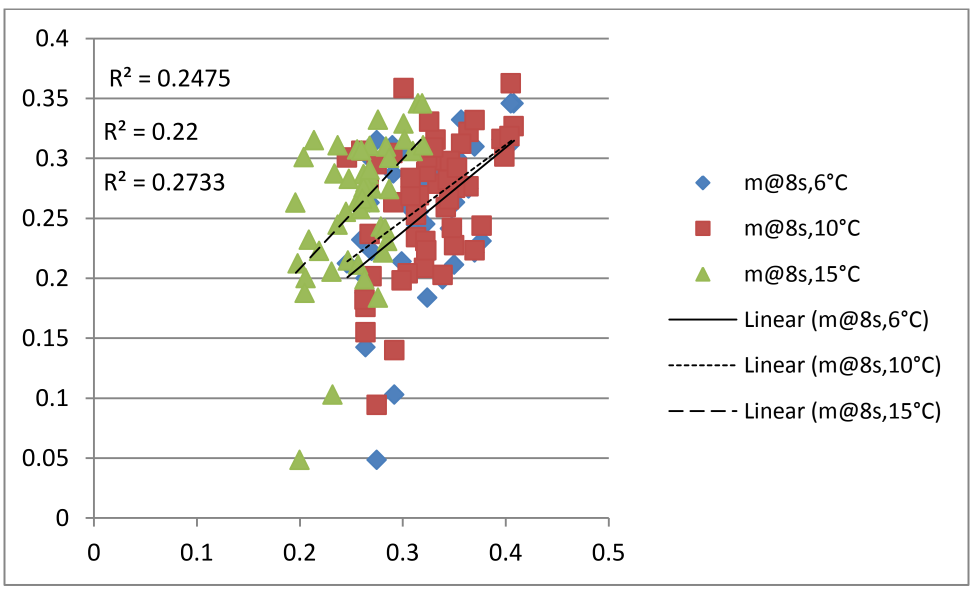


Figure 23: Comparison of Measured (BBR) and Predicted (Frequency Sweep) m-values at 8 s Loading Time

These results can be improved by conducting the BBR tests at a higher temperature (higher than -12°C) and the frequency sweep tests on a machine capable of temperatures lower than 5°C. However, the correlation between the predicted and measured S values is promising. With additional data, the frequency sweep test can be used to develop parameters to replace the S and m-values obtained from the BBR for characterizing the low-temperature performance of binders.

Binder SPG Grading Results

In the existing SPG specification, the G*/Sin δ threshold value at the higher temperature limit was set at 0.65 kPa based on validation of experimental results in previous studies. Further, the threshold values for maximum creep stiffness, S, and minimum m-value measured in the BBR test were set at 500 MPa and 0.24, respectively. The SPG grade of each binder tested was determined on the basis of these criteria. In addition, for a binder to be considered as demonstrating adequate performance in the laboratory, the strain level at $0.8G_i^*$ in the strain sweep test should be at least 25% according to the existing specification (Table 2).

Of the 30 HSs, about 43% (13/30) of the binders tested meet the pavement surface temperature criteria (i.e., satisfy the expected environmental demand at the HS at 98% reliability) and 57% (17/30) do not meet the criteria. These results are illustrated in Figure 24 and are summarized in Appendix A. Binders that meet the temperature criteria are expected to demonstrate adequate performance in the field, while those that fail are expected to exhibit inadequate performance. The SPG specification can be considered valid if this is true.

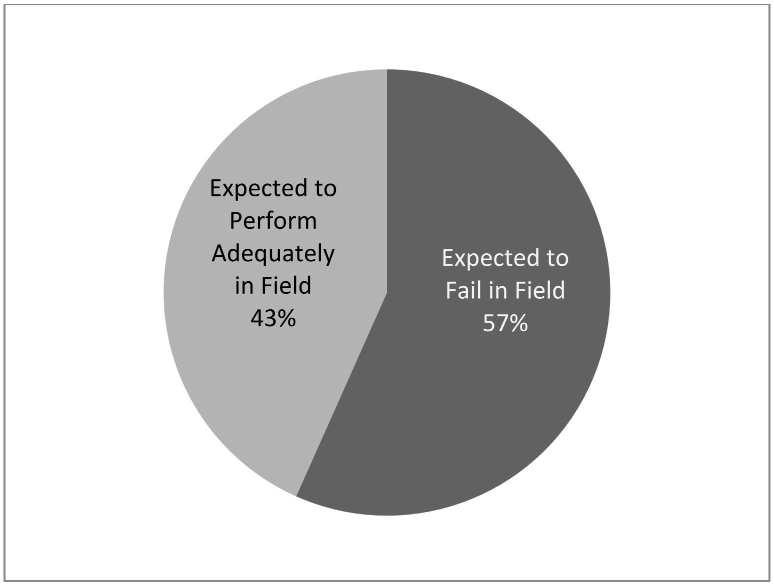


Figure 24: SPG Test Results

All 17 of the binders that fail to meet the SPG temperature criteria fail at the lower temperature limit. Most of these binders failed to meet the BBR m-value limit at the low-temperature limit. Most of the sections with AC15P and AC20-5TR binders meet the SPG criteria. The two CRS-2 samples failed at both the high temperature limit and the low temperature limit. All three AC10 samples also failed the SPG criteria at both temperature limits. Four CRS-2P samples and six AC20-5TR samples fail the SPG criteria at the low temperature limit. Of the 16 AC20-5TR samples tested, only six samples failed at the low temperature limit, as can be seen in Appendix A. Of the 17 samples that failed at the low temperature limit, five failures were unmodified binders, four failures were for CRS-2P binders, and the rest were for AC20-5TR binders. The temperature ranges in this section and in Appendix A refer to the average temperature values obtained from the nearest weather station to a particular HS rather than the generalized average temperature ranges for the respective TxDOT districts (Table 10). The temperatures from the weather stations closest to the HSs selected in this project for SPG analysis are listed in Appendix A.

Effects of Binder Type on SPG Grading

Generally, AC20-5TR materials, followed by CRS-2P and AC15P binders, exhibited superior SPG grades in terms of the DSR high temperatures at the prescribed SPG threshold values. The highest and lowest SPG grade temperatures measured for AC20-5TR were 79°C and -22°C, respectively. At the higher temperature limit, the lowest measured SPG grade temperature was 64°C (CRS-2 and AC10 binders). The highest temperature measured at the lower temperature limit was -10°C (CRS-2 binders). Difference in SPG grades among different binder types alone does not indicate differences in field performance, which can be affected by many influencing factors. Of the binders that fail to meet the SPG criteria, 47% were AC20-5TR binders, as shown in Figure 25. An extract from Appendix A for this binder is shown in Table 16.

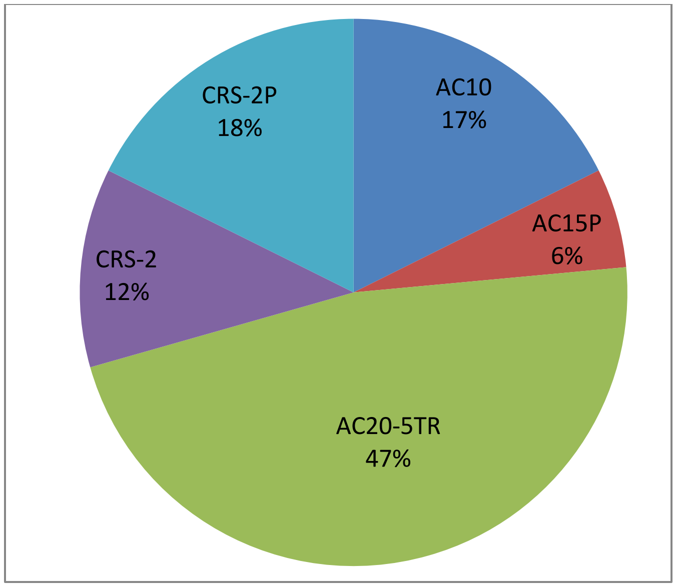


Figure 25: Binders that fail SPG Temperature Criteria

Table 16: Examples of SPG Binder Grade Failures

HS ID	Binder Type	SPG Grade	Environment (°C)	Comment
B-1	CRS-2	64-10	70-22	Failed at both high and low temperature limits
B-2	CRS-2	67-13	70-19	
A-1	AC 20-5TR	70-13	67-19	Failed at low temperature limit
A-6	AC 20-5TR	67-16	67-19	
A-2	AC 20-5TR	67-16	67-16	Passed at both temperature limits
L-1	CRS-2P	76-19	67-16	

It is unclear why some modified binders (AC20-5TR and CRS-2P) exhibited inadequate performance in the laboratory, while other similar binders successfully met the SPG temperature criteria. All the modified binders that fail the SPG criteria fail at the lower temperature limit. The modified binders that failed the SPG criteria in the laboratory were observed to demonstrate an adequate overall field performance, as discussed later in this chapter. In four cases (for binders from HSs B-6, L-4, P-2, and S-3), failure to meet the SPG specification is because of the temperature grade increment used to round temperatures in the SPG grade and not because of the insufficient performance of the binder itself. Further, it is possible that the particular modified binder samples that failed the BBR criteria were of inferior quality. The quality of the modifiers used or the effects of transportation and storage could have caused the failure of these binders in the laboratory tests.

Furthermore, binders classified as the same type exhibited different grades according to the SPG specification. This can be attributed to differences in production, additives and modifiers used, and quality of the binders. A typical example is shown in Table 17 for AC20-5TR binders. Based on the principles of SPG, it can be concluded that the binder from HS A-1 is of lower quality than the binder from HS L-3. The former material can be expected to withstand a narrower range of temperatures than the latter. However, other factors may affect the performance of these binders in the field.

Table 17: Differences in SPG Grade for Same Binder Type

HS ID	Binder Type	SPG Grade
A-1	AC20-5TR	70-16
L-3	AC20-5TR	73-16

Environmental Temperatures and Binder Grade Increment

As mentioned previously, some binders failed to meet the SPG temperature criteria because of the 3°C grade increment. For instance, the AC20-5TR binder on HS B-6 has an SPG grade of SPG 76-16 and failed at the low temperature limit in an environment of 67-18°C at 98% reliability but passed when tested at -18°C (S<500 MPa and m-value>0.24). However, it was not possible to grade this binder as SPG 76-18 because the 3°C temperature increment does not include this limit (-18°C) in the grading system. Therefore, the binder has to be graded as SPG 76-16, which appears to be a failure at the lower temperature limit, although the binder meets the environmental temperature demand. Although the SPG specification shows failure, actual field performance could be adequate. As discussed subsequently, HS B-6 performed relatively well with an overall SCI score of 82%. However, in some cases, the inferior quality of the binder sample could have caused failure in the laboratory tests, as evidenced by the adequate performance of other AC20-5TR binders in these tests.

Field Performance Monitoring Results

Visual condition surveys were performed on 29 field sections once at construction and once after the first summer and winter after construction. Eighty seven percent (27/31) of the HSs exhibited adequate performance (with SCI equal to or greater than 70%) in terms of the combined weighted distresses of aggregate loss and bleeding. Thirteen percent (4/31) exhibited inadequate performance (SCI less than 70%). None of the emulsions included in this study exhibited distress in the form of bleeding. However, both sections with CRS-2 fail due to aggregate loss. Inadequate resistance to bleeding was observed in four sections that received surface treatments with AC10, AC15P, and AC20-5TR binders. Aggregate loss was observed in sections with CRS-2, CRS-2P, AC15P, and AC20-5TR binders.

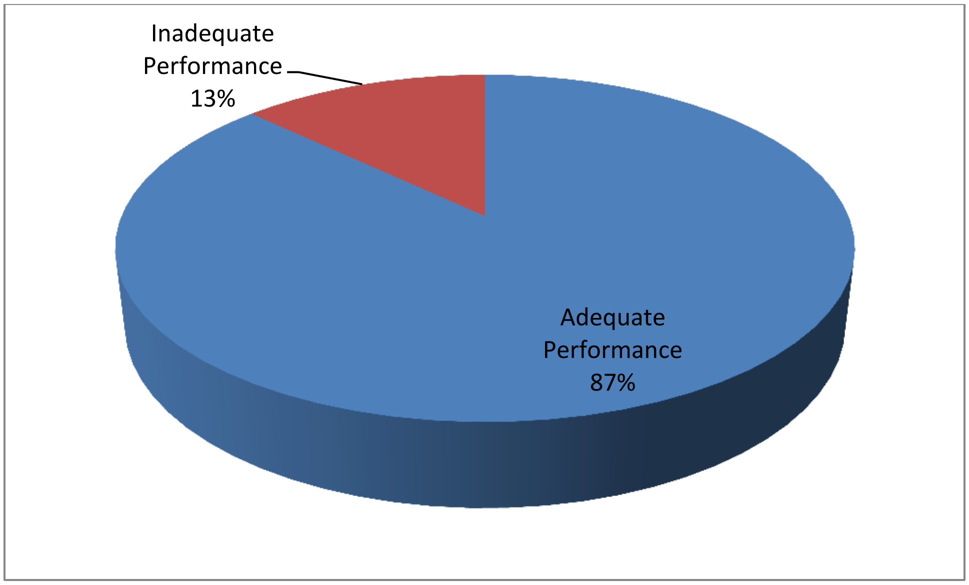


Figure 26: Field Performance Monitoring Results

This section presents some examples of adequate and inadequate performance in relation to the binders used. Other factors that may impact surface treatment performance are also discussed. These include environmental conditions, aggregates, traffic, and existing pavement conditions prior to the surface treatment. Factors such as design, construction, and quality control that may also affect the performance of surface treatments were beyond the scope of this study.

Example of Adequate Performance, SCI = 70%

Almost all the binders included in this study exhibited adequate overall performance in the field. Under similar climatic conditions, for example, in the Brownwood district, the decreasing rank order of performance was CRS-2P, AC20-5TR, and CRS-2. No significant distresses were recorded on the HSs with CRS-2P binders in this district. An example of adequate field performance is shown in Figure 27 for HS A-4.

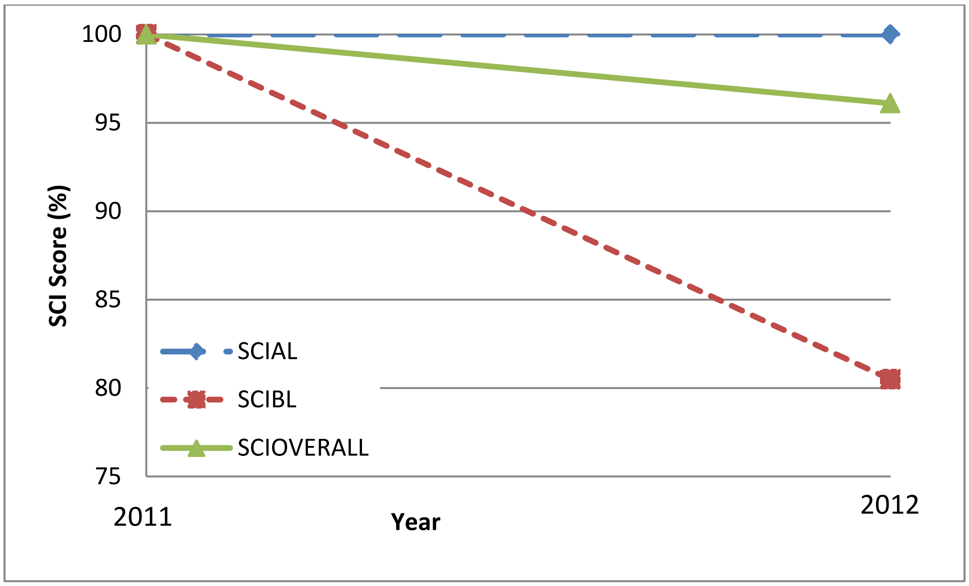


Figure 27: Example of Adequate Performance—HS A-4

The performance of HS A-4 is adequate both in terms of the individual distresses and the overall combined distress with SCI scores greater than 70%. The overall SCI score for this section is 96%. This is also reflected in the digital picture of the section in Figure 28. The materials used on this section were AC20-5TR and sandstone aggregate. This section is located in an environment of 67-16°C at 98% reliability. The ADT was approximately 2000 on this section.

Figure 28: Example of Adequate Performance—HS A-4

Example of Inadequate Performance, SCI < 70%

The four HSs that demonstrated inadequate performance received surface treatments with CRS-2, CRS-2P, and AC20-5TR binders. Figure 29 and Figure **30** show an example of inadequate performance in terms of aggregate loss (SCI_{AL} = 51%) for HS B-1. This section received a surface treatment with CRS-2 binder and limestone aggregate. The ADT on this section was recorded at approximately 270. This section experiences temperatures in the range of 70-22°C at 98% reliability.

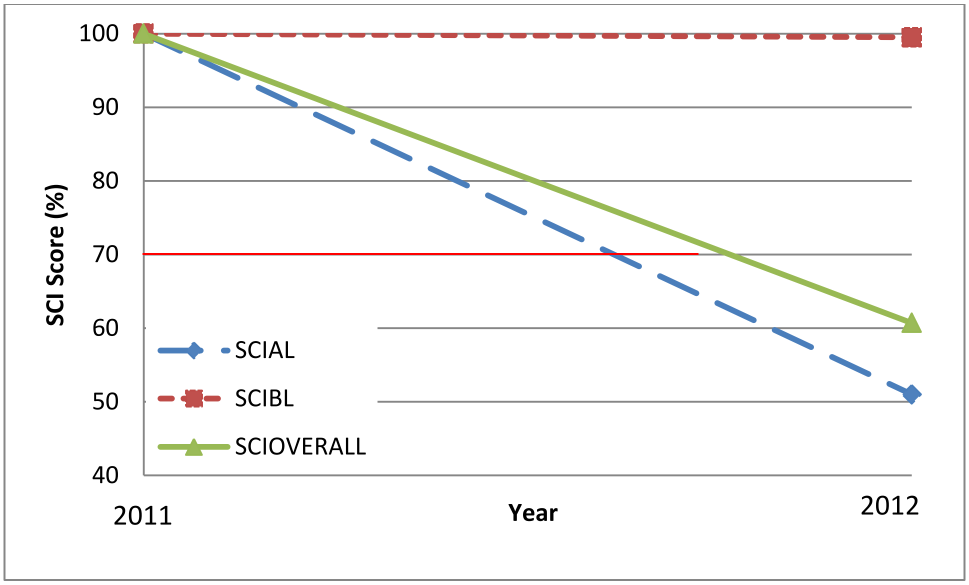


Figure 29: Example of Inadequate Performance—HS B-1

Figure 30: Example of Inadequate Performance—HS B-1

Effects of Aggregates on Performance

Most of the sections monitored in the SPG study were constructed with precoated aggregates. The effect of precoating on aggregate retention has been found to vary with the aggregate material type (Rahman et al. 2012). Sections with limestone, gravel, and limestone rock asphalt aggregates appeared to exhibit better field performance than sections with lightweight and sandstone aggregates. Most of the sandstone, limestone, and lightweight aggregates were precoated. Further, because of the relatively low traffic levels in the Childress sections, HSs with gravel appear to perform considerably better ($SCI_{OVERALL}$ > 93%) than most of those with precoated aggregates (lightweight, limestone, and sandstone). It should be noted that precoated aggregates have been found to perform better than uncoated aggregates in the past and have been recommended for improving binder-aggregate adhesion. This trend was also observed in the case of sections from TxDOT Project 1710; most of the sections that are performing adequately 10 years after construction in this study were constructed with pre-coated aggregates.

Effects of Traffic on Performance

Sections with high traffic levels exhibited distresses in the form of bleeding as well as aggregate loss. The section with the highest volume of traffic in this study, HS A-5, exhibited severe bleeding. Aggregate embedment was also very high in the wheelpath for this section and for others with high traffic levels. HS A-5 received a surface treatment with AC 20-5TR binder and PB/PL aggregate. The ADT on the section was approximately 7550, and it experienced temperatures in the range of 67-16°C at 98% reliability. Its performance was inadequate in terms of bleeding with an SCI_{BL} score of 36%. HS A-6, which faced similar traffic levels with an ADT of 7440, failed because of aggregate loss (SCI_{AL} = 67.5%). This section was constructed with the same binder and aggregate type as HS A-5. The condition of HS A-6 one year after construction is shown in Figure 31.

Figure 31: Field Performance under Heavy Traffic—HS A-6

Effects of Existing Pavement Condition on Performance

One of the pre-existing conditions that affected the performance of the surface treatments was cracking in the underlying structure. For example, HSs P-3 and P-4 exhibited longitudinal and transverse cracks, as can be seen in Figure 32.

Figure 32: Example of Longitudinal and Transverse Cracks on HS P-3

These sections also exhibited poor performance in terms of aggregate loss and bleeding one year after the application of the surface treatment: HS P-3 has an SCI_{AL} score of 59% and HS P-4 nearly fails due to bleeding with an SCI_{BL} score of 76.

Aggregate Embedment

For the HSs surveyed in this study, aggregate embedment ranged between 20 and 95% in the wheelpath and 10 to 80% between the wheelpaths. High aggregate embedment was usually accompanied by bleeding. Further, aggregate embedment was often high on HSs with high traffic volumes.

The SPG Specification versus Field Performance

A comparative analysis of the laboratory and field performance results is presented in this section. For about 51 (15 of 29) percent of the HSs, the SPG binder grade predictions based on the laboratory results were correlated with field performance. Of these sites, 13 sections showed adequate field performance while two exhibited inadequate performance. The large number of laboratory failures at the low temperature limit adversely affected the correlation between the laboratory and field results.

Conversely, about 49% (14 of 29) of the HSs did not exhibit field performance that correlated with the laboratory predictions. Of these, the two sections that failed were treated with AC20-5TR and CRS-2 binders. The SPG predicted adequate performance in the laboratory when the field performance was inadequate for only 6% of the HSs. Further, for about 40% of the HSs, field performance was, in fact, adequate (SCI greater than 70%) when the laboratory results predicted otherwise. These results are summarized in Appendix B.

For a laboratory result to be classified as ‘Pass’, the corresponding binder must meet the HS environmental demand at a reliability level of 98% (for example, HS L-1 has a binder graded as SPG 76-19, while the environmental demand of the section is 67-16°C). In contrast, a laboratory result is classified as ‘Fail’, when the binder does not meet the environmental demand of the HS at the 98% reliability level (for example, HS A-1 has a binder graded as SPG 70-13, while the environmental demand of the section is 67-19°C). If a binder falls under the ‘Fail’ category, it may be unsuitable for use in the expected temperature conditions at the HS.

Binders were classified as 'Pass' or 'Fail' on the basis of the key SPG parameters (Table 1)—*G*/Sin δ*, *S*, and *m-value*—relative to the corresponding environment conditions at a 98% reliability level (Appendix B).

Field performance results are classified as 'Pass' if the HS performs adequately with limited or no visual distresses represented by an SCI score equal to or greater than 70%. In contrast, 'Fail' indicates inadequate performance of the surface treatment and an SCI score of less than 70%. Field results were categorized using these criteria in terms of aggregate loss (indicated by an SCI_{AL} of less than 70%), bleeding (indicated by SCI_{BL} of less than 70%), or overall performance (indicated by $SCI_{OVERALL}$ of less than 70%).

Laboratory and field performance results were considered to be correlated when a 'Pass' according to the SPG laboratory criteria matched a 'Pass' in terms of field performance, or when a 'Fail' in the laboratory tests corresponded to a 'Fail' in the field observations. Further, the results were considered to be not correlated when a 'Pass' in according to laboratory results matched a 'Fail' according to the field observations or a 'Fail' according to the laboratory results matched a 'Pass' in the field. The most concerning results are those in which a binder is categorized under 'Pass' in the laboratory but exhibits inadequate performance in the field and is classified as 'Fail'. A comparison of the SPG laboratory versus field performance results is summarized in Appendix B. The comparative analysis between the SPG laboratory results and the field performance results are discussed subsequently.

Good Correlation: Pass (SPG) – Pass (Field Performance, SCI ≥ 70%)

The SPG grade based on the laboratory results and the field performance results were both found to be adequate for HS A-4, as shown in Figure 33 and Figure 34. The binder grade obtained from the SPG laboratory tests was SPG 73-16, which satisfies the expected environmental demand (67-16°C) for the HS at 98% reliability. This laboratory result predicts adequate performance in the field (Pass) and is consistent with the observed adequate field performance (Pass). The HS received an overall SCI score of 96.1%, which correlates with the SPG binder grade obtained from the laboratory results. Similar results were obtained for 12 other HSs (Appendix B).

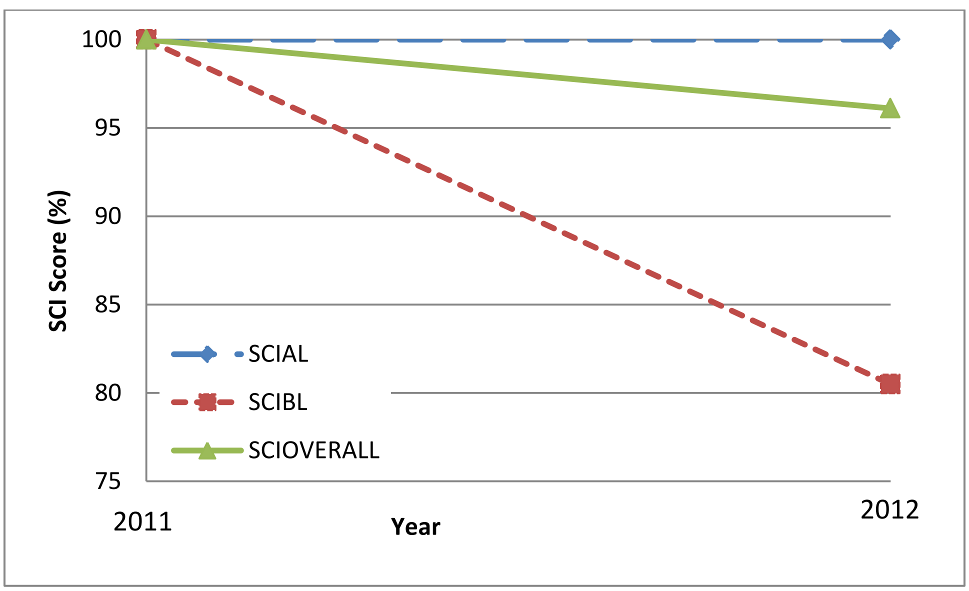


Figure 33: Adequate Performance on HS A-4 ($SCI_{OVERALL}$ = 96%)

Figure 34: Example of Adequate Performance—HS A-4

HS A-4 received a surface treatment with AC20-5TR and precoated sandstone aggregate. The ADT observed on this section was approximately 2000. Material application rates were 0.34 gallons per square yard (gal/sy) of binder sprayed at 182°C and 1/113 cubic yard per square yard (cy/sy) of aggregate at the time of construction. These design and construction parameters are consistent with TxDOT recommendations.

Although the overall SCI score and the SPG grading results are correlated for all of these sections included in this category, two sections (A-5 and S-5) demonstrate inadequate resistance to bleeding (SCI_{BL} of 36% and 63.5%, respectively). Because of the low weight (20%) assigned to SCI_{BL} in calculating the overall SCI and because of superior performance in terms of aggregate retention, HSs A-5 and S-5 received sufficiently high $SCI_{OVERALL}$ scores (87% and 91.9%, respectively). HSs A-5 and S-5 were constructed with AC20-5TR and AC15P binders, respectively. These binders exhibit adequate performance in the laboratory, with an adequate SPG grade, a sufficiently high strain sweep parameter (percent strain @ $0.8G_i^* > 25\%$), and adequate MSCR parameters (J_{nr} @ 0.1 kPa < 0.3 kPa^{-1} and percent recovery > 60%). Therefore, it was concluded that HSs A-5 and S-5 demonstrate inadequate resistance to bleeding in the field because of the very high traffic volumes on these sections (ADT of 7550 and 5571, respectively)

Good Correlation: Fail (SPG) – Fail (Field Performance, SCI < 70%)

The SPG grade predictions matched the field performance for another set of field sections. Two HSs (B-1 and B-2) (Appendix B) exhibited inadequate performance in the field (Fail) and had SPG laboratory results that predicted such performance (Fail). These sections received surface treatments with CRS-2 binders. These binders had laboratory SPG grades that are inadequate for the environmental demand expected at the corresponding sections. Further, these binders also failed to perform in the field with SCI scores of less than 70%. Figure 35 shows the SCI scores for HS B-2, and Figure 36 shows an example of the distresses observed at the section. The distresses observed for HS B-1 are shown in Figure 29 and Figure 30.

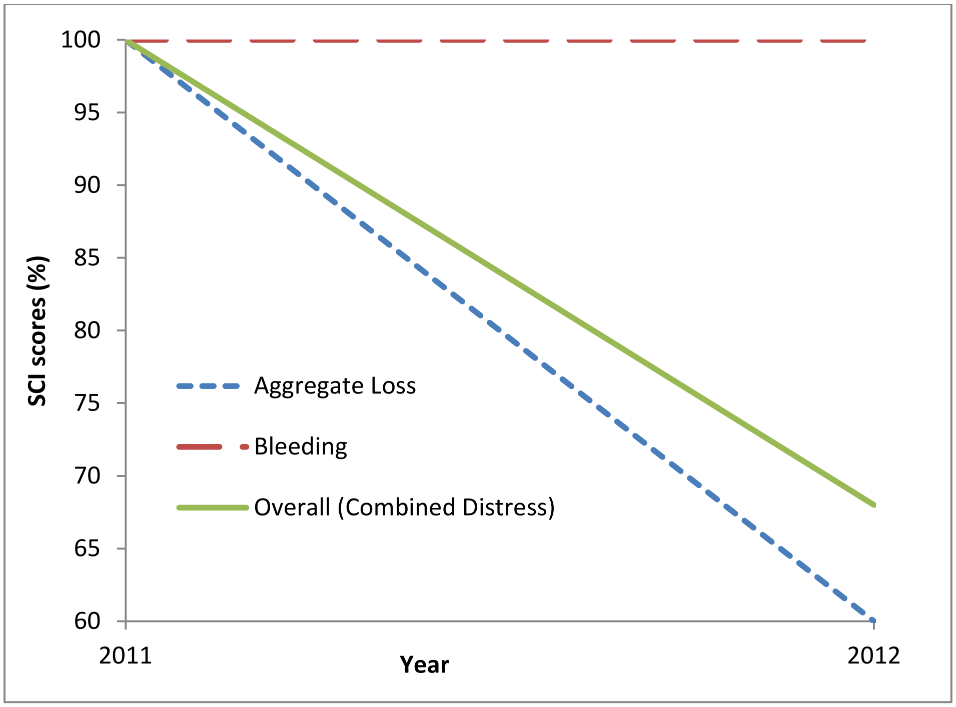


Figure 35: Inadequate Performance on HS B-2 ($SCI_{OVERALL}$ = 68%)

Figure 36: Example of Inadequate Performance on HS B-2

HS B-2 received a surface treatment with CRS-2 binder and precoated limestone aggregate. The CRS-2 binder had a laboratory binder grade of SPG 67-13, which fails to meet the expected temperature range of 70-19°C at 98% reliability. This Fail in terms of SPG specification corresponds to a Fail in terms of field performance, with the HS having an overall SCI score of 68 (less than 70). Aggregate loss was more predominant than bleeding on this section.

In addition to the properties of the binder, construction quality, material application rates, and quality control problems may have added to the inadequate performance of this field section. The material application rates were 0.44 gal/sy of binder sprayed at 185°C and and 1/100 cy/sy of aggregate.

No Correlation: Pass (SPG) – Fail (Field Performance, SCI < 70%)

Two HSs (L-1 and P-3) exhibited inadequate performance in the field (Fail) but were constructed with binders that passed the SPG temperature specification (Pass). HS L-1 and P-3 received treatments with CRS-2P and AC20-5TR binders, respectively. These binders meet the expected environmental demand at the sections according to the SPG laboratory results, but the corresponding HSs perform poorly with SCI scores less than 70%. Both the sections fail because of excessive aggregate loss. In addition, minimal bleeding was observed on HS L-1. An example of a Pass in the SPG specification and Fail in the field (HS L-1) is demonstrated in Figure 37 and Figure 38.

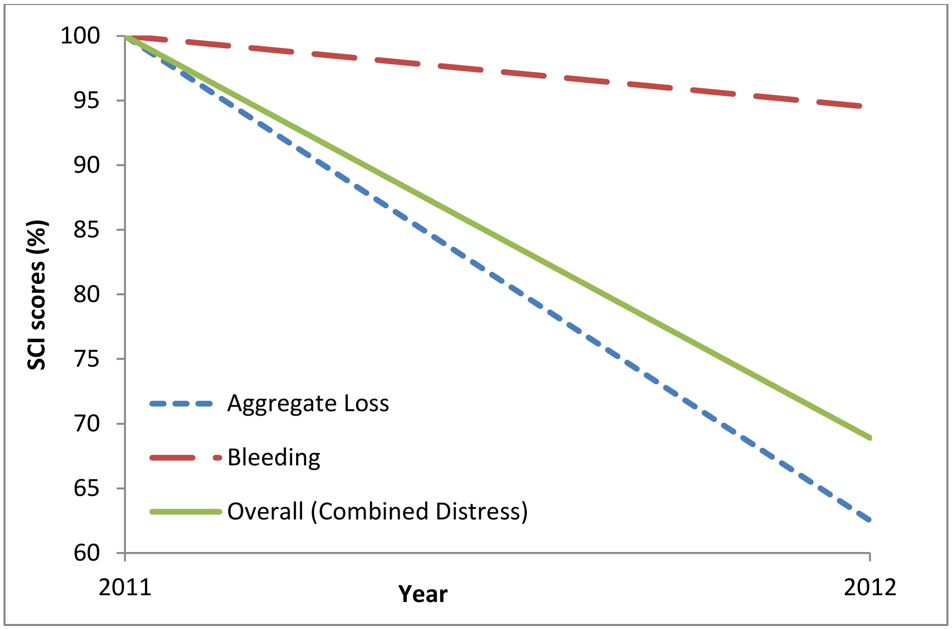


Figure 37: Inadequate Performance on HS L-1 ($SCI_{OVERALL}$ = 69%)

Figure 38: Example of Inadequate Performance on HS L-1

The AC20-5TR binder on this section had an SPG grade of SPG 76-19, which meets the environmental temperature demand of 67-16°C at 98% reliability. The section was constructed with lightweight aggregates. The ADT on this section was approximately 600. The material application rates were 0.4 gal/sy of binder sprayed at 175°C and 1/100 cy/sy of aggregate.

The discrepancy in the SPG grading and field performance results for HS L-1 can be explained by other laboratory results. The CRS-2P binder on this section did not meet the prescribed strain sweep criterion in the modified SPG specification (percent strain @ $0.8G_i^* < 25\%$). The steep slope of the strain sweep curve for this binder indicates inadequate strain tolerance, which might have caused aggregate loss on HS L-1. Further, although the AC20-5TR binder on HS P-3 performs adequately in all the laboratory tests, the high traffic volume (ADT = 3900 veh/day) on this section could have caused performance problems in the field.

No Correlation: Fail (SPG) – Pass (Field Performance, SCI ≥ 70%)

In this study, 12 sections demonstrated adequate field performance (SCI ≥ 70%) but received surface treatments with binders that performed inadequately in the laboratory tests. Of these 12 sections, 6 sections had AC20-5TR binders. The other binders that failed according to the SPG temperature specifications but performed adequately in the field were CRS-2P and AC10 binders.

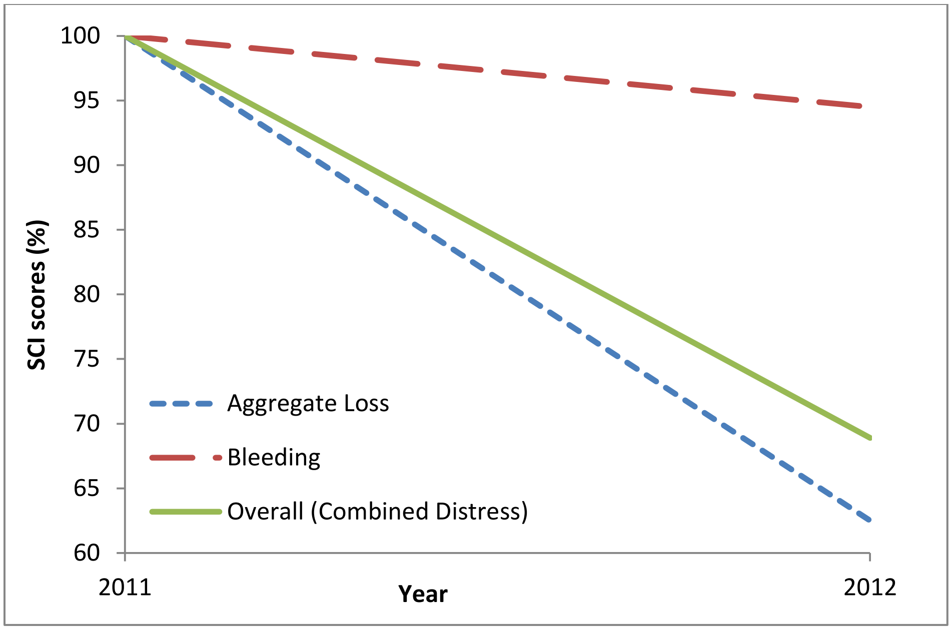


Figure 39: Inadequate Performance on HS P-2 ($SCI_{OVERALL}$ = 96%)

Figure 40: Example of Inadequate Performance on HS P-2

For example, HS P-2 had an overall SCI score of 95.6% (Figure 39 and Figure 40), while the CRS-2P binder on this section has an SPG grade of SPG 70-16 in an expected environment of 67-19°C at 98% reliability.

The aggregate on HS P-2 was precoated limestone, and the ADT was approximately. The possible cause of the lack of correlation between the laboratory and field observations could be the very low traffic volume on this section. Low traffic levels (ADT<3000 veh/day) could also explain the discrepancy in results for six other sections (C-3, C-2, A-1, C-1, B-3, and B-4). It could be expected that the distresses expected on these sections owing to the binder properties will appear over time with increasing traffic and age.

Additionally, for four sections in this category, although the overall SCI score was greater than 70, the SCI scores for individual distresses was inadequate. HSs A-6 and P-6 have SCI_{AL} scores of less than 70% (67.5 and 65%, respectively). Further, HSs C-2 and L-4 have SCI_{BL} scores of less than 70% (68 and 64%, respectively). However, because the overall SCI score is a weighted average of SCI_{AL} and SCI_{BL}, these sections receive adequate $SCI_{OVERALL}$ scores and are classified as 'Pass' in field performance. It should be noted that HSs A-6 and P-6 experienced high traffic volumes (ADT of 7440 and 5881, respectively). Further, the AC20-5TR binders on these sections failed the BBR test criteria in SPG grading, which could have caused aggregate loss problems at the low temperatures these pavements experienced. Similarly, HSs C-2 and L-4 were constructed with AC10 and AC20-5TR binders, respectively, which failed the SPG low-temperature criteria and have very low J_{nr} percent recovery values (3.3% and 23.8%, respectively). Moreover, the AC10 binder on C-2 failed the SPG high-temperature criterion in addition to the low-temperature criteria. These inferior binder properties observed in the laboratory could have caused the failure of these sections in bleeding in the field. In addition, the high traffic volume (ADT = 4400 veh/day) on HS L-4 could have contributed to the distress observed on the section.

Furthermore, the AC20-5TR binder on HS B-6 fails to meet the SPG low-temperature criteria because of the 3°C grade increment, but, in fact, meets the expected environmental demand for the section. This could be the reason for the overall SCI score of 82% for this section. Additionally, inconsistency in the quality of the sampled AC20-5TR binder on HS B-5 and other binders can be the reason behind the differences in performance in laboratory tests and the field.

Discussion

Given the random selection of the pavement sections based on construction schedules and the lack of control over construction practices and design modifications, these results are valid and can be used to improve the SPG specification. The discrepancies in laboratory and field results discussed in the previous section can be addressed by adjusting the existing SPG specification and adding additional parameters. While the section-specific causes of these discrepancies have been discussed in the previous section, further reasons for inconsistent field performance results are presented subsequently.

Material Quality and Testing Procedures

In addition to the properties of the binders and the aggregates used in the surface treatments, the quality, sampling, transportation, and storage of the materials as well as the test method employed could have created differences between observed performance in the laboratory and the field.

Poor Material Quality

Some laboratory failures in terms the SPG temperature criteria could have been because of the poor quality of the binders sampled. A wide variation was observed in the laboratory SPG grade of AC20-TR binders from the same supplier for sections in the same district (Atlanta). The AC20-5TR binders applied on HS A-1 and A-6 failed to meet the SPG low-temperature criteria, while other AC20-5TR binders in the same environmental zone passed the SPG tests. However, all the sections with these binders exhibited adequate performance in the field.

Time, Transportation, and Storage Effects

While most of the binders were tested as soon as possible after sampling, the BBR test could not be performed on some samples until later in the study owing to technical problems with the testing equipment. This delay in testing could have contributed in inaccurate results. Further, the materials could have been adversely affected by transportation and segregation during storage, despite the care taken to store the binder samples at cold temperatures.

Characterization of Aged Binder Properties

In order to characterize the low-temperature properties of the emulsion residues and hot-applied binders tested in this study, the binders were aged in the PAV for 20 h at 100°C. This laboratory aging of the binders in the PAV is believed to simulate approximately one year of aging in the field for surface treatments (Epps Martin et al. 2001; Walubita and Epps Martin 2005b). However, further validation of this relationship might be required to ensure that aging is simulated accurately.

Further, the possibility of replacing the low-temperature BBR test with the intermediate-temperature DSR frequency sweep test has been explored in this study. By grading the binders using the S and m-value predicted from the frequency sweep results, it was found that only 11 of the 30 binders failed to meet the SPG temperature criteria. The binders (CRS-2P, AC15P, and AC20-5TR) from HSs B-3, L-4, P-1, P-2, P-3, and S-3 failed to meet the low-temperature criteria when graded using measured BBR values but passed the criteria when graded using the predicted BBR values. Further, except for HS P-3, these sections exhibited adequate field performance. Using the predicted BBR results also reduces the number of laboratory failures among modified binders. It might be possible to obtain more values suitable for reliably predicting the BBR parameters at much lower temperatures with a more versatile DSR instrument. The relationship between frequency sweep results and BBR results should be further investigated in future studies.

SPG Grading Temperature Increment

Some binders failed to meet the SPG temperature criteria in the laboratory tests because of the 3°C grade increment. This problem was illustrated earlier in this chapter with the example of HS B-6. Although some binders meet the required environmental demand at the corresponding HSs, they could not be graded at those intermediate passing temperatures because of the SPG temperature increment. However, this would be a problem regardless of the size of the temperature increment used and cannot be avoided without creating a large number of SPG grades. Nevertheless, it must be noted that the lack of correlation between the laboratory and field results could be, in part, because of this grading procedure. Further, by rounding up the required temperature values and rounding down the laboratory grade, the SPG specification introduces additional conservatism. The use of continuous grading as described in ASTM D7643, as opposed to the SPG grading, would allow a more robust comparison of the results.

Field Performance Evaluation

Despite its simplicity and clarity, the visual survey-based performance evaluation system used in this study is subjective. Particular care was taken to use the same evaluator for the two sets of inspections to improve the consistency of the results. Further, two to four test sections were monitored for each HS to obtain a more complete and accurate picture of the field performance. In addition, digital images of the surveyed sections were collected at the time of the survey, allowing the verification of recorded distress levels. Therefore, it is expected that the performance evaluation method itself did not adversely affect the field performance results in this study.

Additionally, two performance monitoring sessions were conducted as part of this study—one at construction and the other one summer and one winter after construction. The two performance monitoring sessions are expected to capture the most critical time in the life of the surface treatment. However, conducting more than two inspections during the study might have provided more insight into the progression of distresses over the first year of the life of the surface treatment.

Design and Construction Practices

The SPG specification is based on the assumption that the material application rates and construction were according to the design and recommended TxDOT standard practices. Further, binder application rates developed in the design should be adjusted for the existing pavement conditions to prevent distresses from reappearing in the new surface treatments. It was observed that the material application rates for most of the sections in this study were uniform throughout a given section and failed to take into account variations in traffic loads in the wheelpath and between the wheelpath. Issues such as these are beyond the scope the project and could not be controlled. This may have caused some sections to perform inadequately. Furthermore, improper construction practices can lead to damage and deterioration in surface treatments despite adequate design and careful selection of construction materials. It is important that the contractors adhere to the design and specification, take into account the weather conditions at the time of construction, and apply the appropriate amount of material with the required level of compaction to achieve a long-lasting surface treatment. Construction practices were also beyond the scope of this study and are assumed to be adequate.

SPG Threshold Values

The temperature criteria included in the existing SPG specification include a minimum value of 0.65 kPa for the DSR parameter, G*/Sin δ at the high temperature limit, and a maximum value of 500 MPa and a minimum value of 0.24, respectively, for the BBR parameters, S and m-value, at the lower temperature limit. These properties were plotted along with the SCI scores (above the data point) and the traffic levels (below the data point) for each HS. In addition, the strain sweep results were compared with the field performance results to develop an improved limiting value for the percent strain parameter based on the larger dataset available in this study. These plots and comparisons are discussed subsequently.

G*/Sin δ

Most of the binders tested in this study had G*/Sin δ values greater than 0.65 kPa, as can be seen in Figure 41. Those binders that fall below the DSR high temperature limit were expected to fail in the field. However, only one of these sections, HS B-1 exhibited inadequate field performance. The other three sections that fail to meet the G*/Sin δ criterion have very high $SCI_{OVERALL}$ values as can be seen from Figure 41. This is possibly because of the low traffic volumes on these sections. The specific reasons for the failures of HSs B-1, B-2, L-1, and P-3 have been discussed in the previous sections. Based on these results, it was decided that the existing G*/Sin δ limit should not be modified.

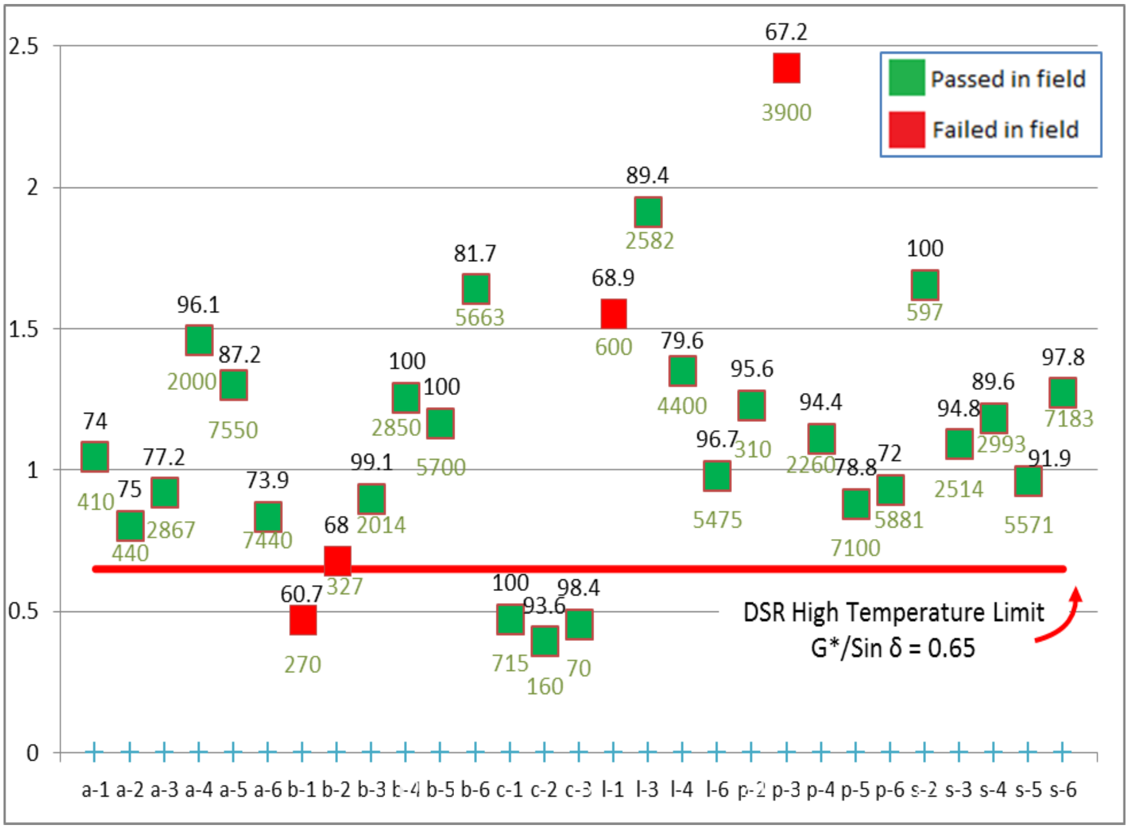


Figure 41: G*/Sin δ for all HSs

Flexural Creep Stiffness and m-value

Figure 42 and Figure 43 show plots of creep stiffness and m-value for all the HSs in this study, along with the $SCI_{OVERALL}$ and traffic volume. As is evident from Figure 42 and Figure 43, most of the binders tested in this study have creep stiffness values that are below the 500 MPa limit at the required lower pavement temperature. As explained earlier, the binders HSs B-4 and C-3 fail in the laboratory, but exhibit adequate performance in the field. This can be attributed to low traffic volumes (ADT<3000 veh/day). The reasons for the discrepancy in the laboratory and field performance results for HSs L-1 and P-3 have been discussed in the previous sections.

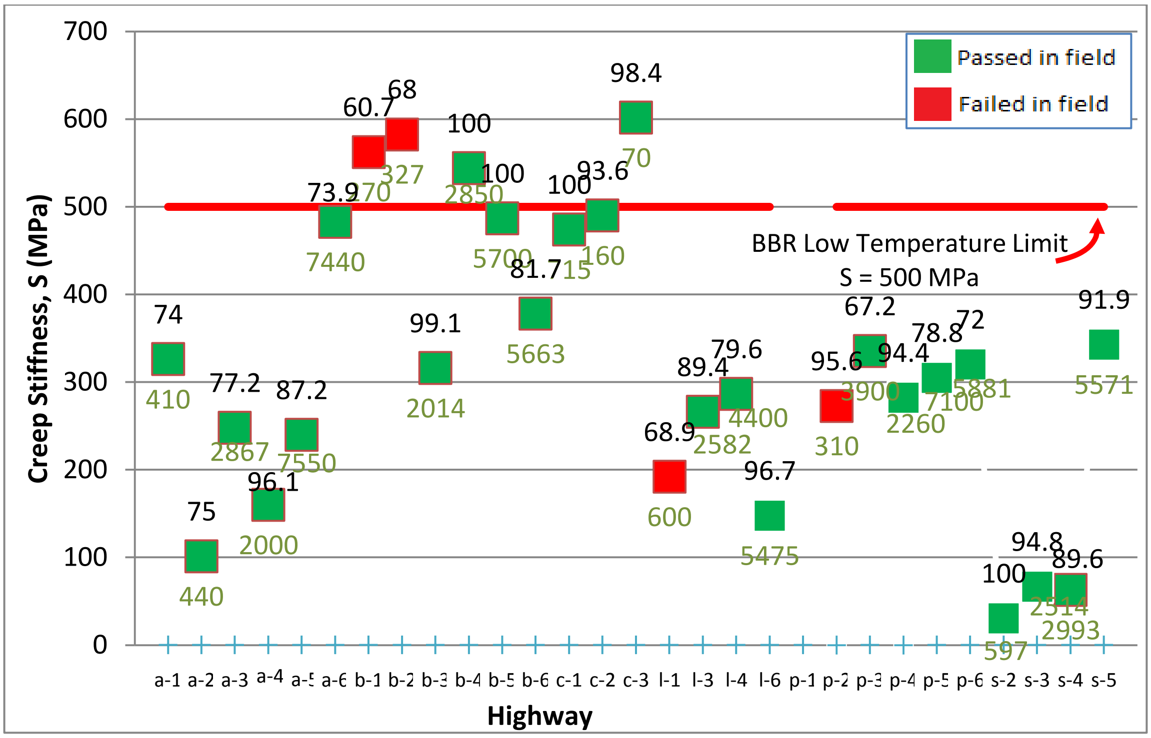


Figure 42: Creep Stiffness for all HSs

Further, Figure 43 showing the m-values indicates that many sections that exhibit adequate field performance fail to meet the existing m-value limit (minimum value of 0.24). Based on the comparison of field and laboratory results, it is suggested that the m-value limit be moved to 0.21. By revising the limiting m-value to 0.21, the number of binders that fail the SPG temperature criteria in the laboratory is greatly reduced from 17 to 7 binders. With the revised m-value, two CRS-2 binders, three AC10 binders, one

CRS-2P binder, and one AC20-5TR binder fail the SPG criteria. Further, the correlation between the laboratory results and the field results increases to 76%.

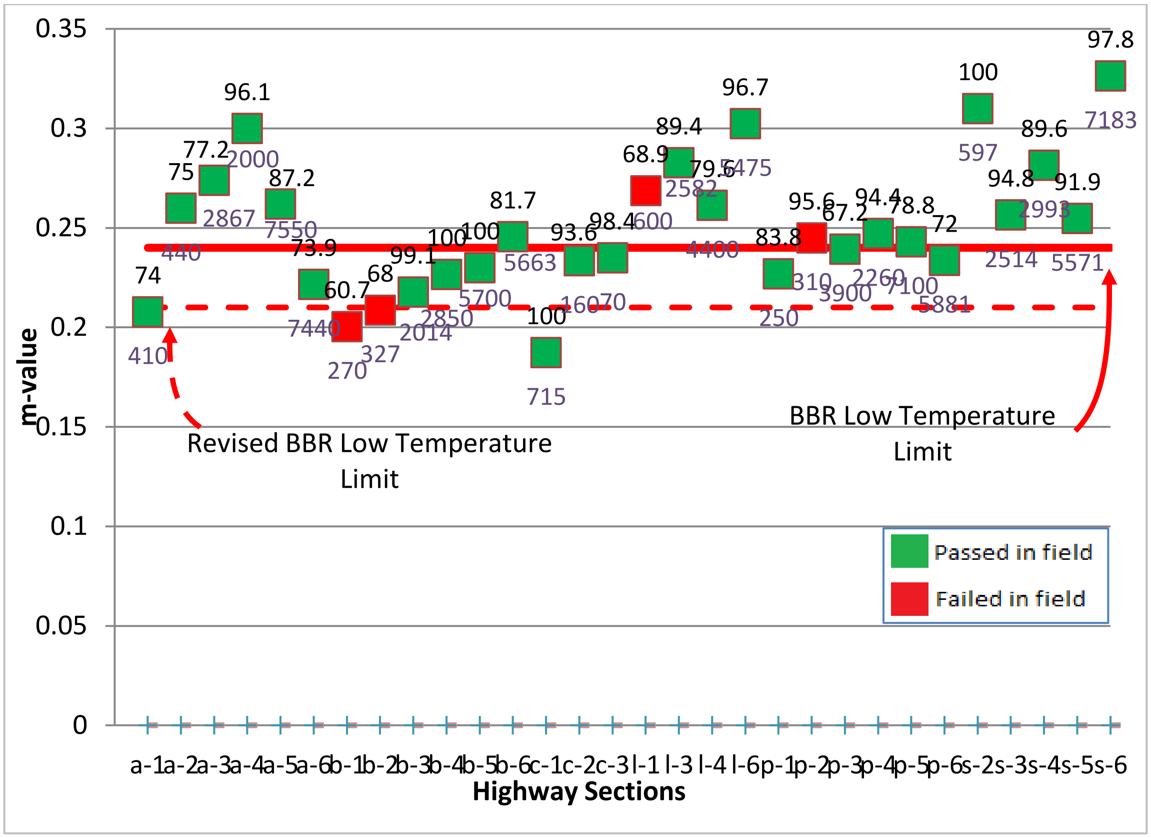


Figure 43: m-value for all HSs

Percent Strain (Strain Sweep Parameter)

As explained earlier, the strain sweep parameter included in the modified SPG specification was validated based on a limited number of pavement sections. Therefore, the limiting value (25%) for the minimum percent strain @ 0.8G_i* does not successfully identify problem binders and appears to be too conservative (Figure 44). The limit for this parameter should be revised to 15% to better relate laboratory failures to field performance failures. With this new limit, most of the sections can be classified as 'Pass' according to both the laboratory and field performance results. HS C-2, which fails the strain sweep criterion despite the revision, has very low traffic and may begin to exhibit distresses in the future.

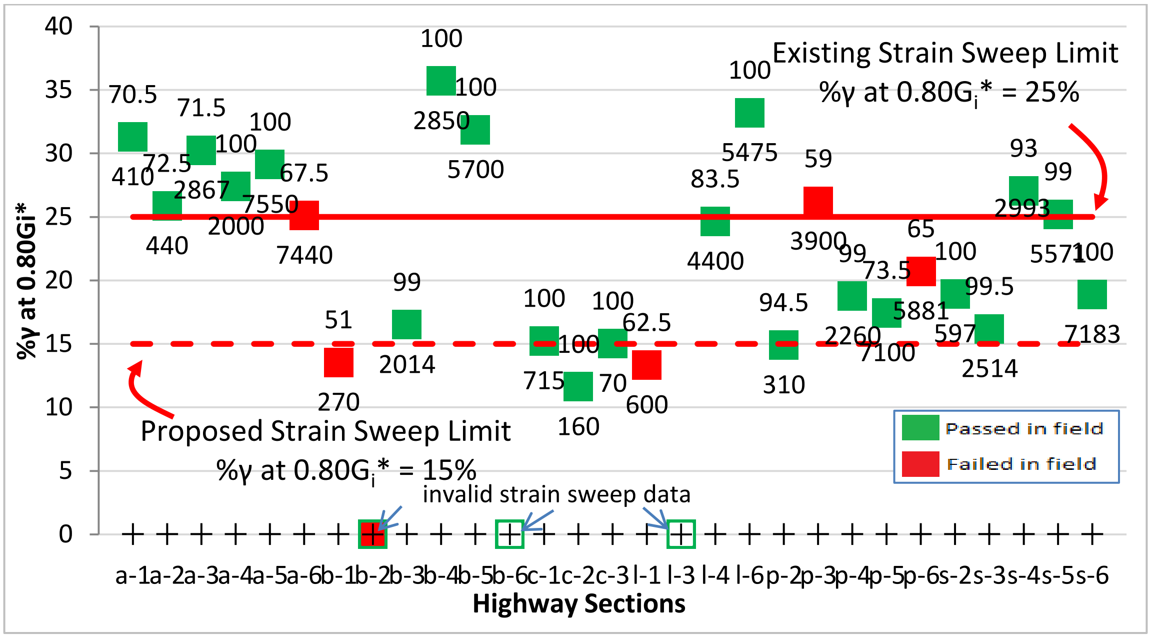


Figure 44: Strain Sweep Results for all HSs

MSCR Parameters

Figure 45 shows the values of J_{nr} at the 0.1 kPa stress level for all the sections surveyed along with the overall SCI and traffic volume. Currently, there does not exist a limiting value for this parameter for surface treatment binders. Based on the typical limits of J_{nr} for HMA pavements, all the binders tested in this study should have adequate resistance to bleeding. However, as can be seen in Figure 45, four sections fail due to bleeding (SCI_{BL} < 70%) even though their overall SCI scores may be adequate.

The reasons for the failure in these sections have been discussed on a case-by-case basis; however, it is challenging to set a limiting value for J_{nr} (and, similarly, percent recovery) given the unsystematic occurrence of bleeding in these sections. It is possible that J_{nr} and percent recovery are not suitable parameters for characterizing the behavior of surface treatment binders. Further testing is required to examine the relationship between MSCR test results and field performance for surface treatments.

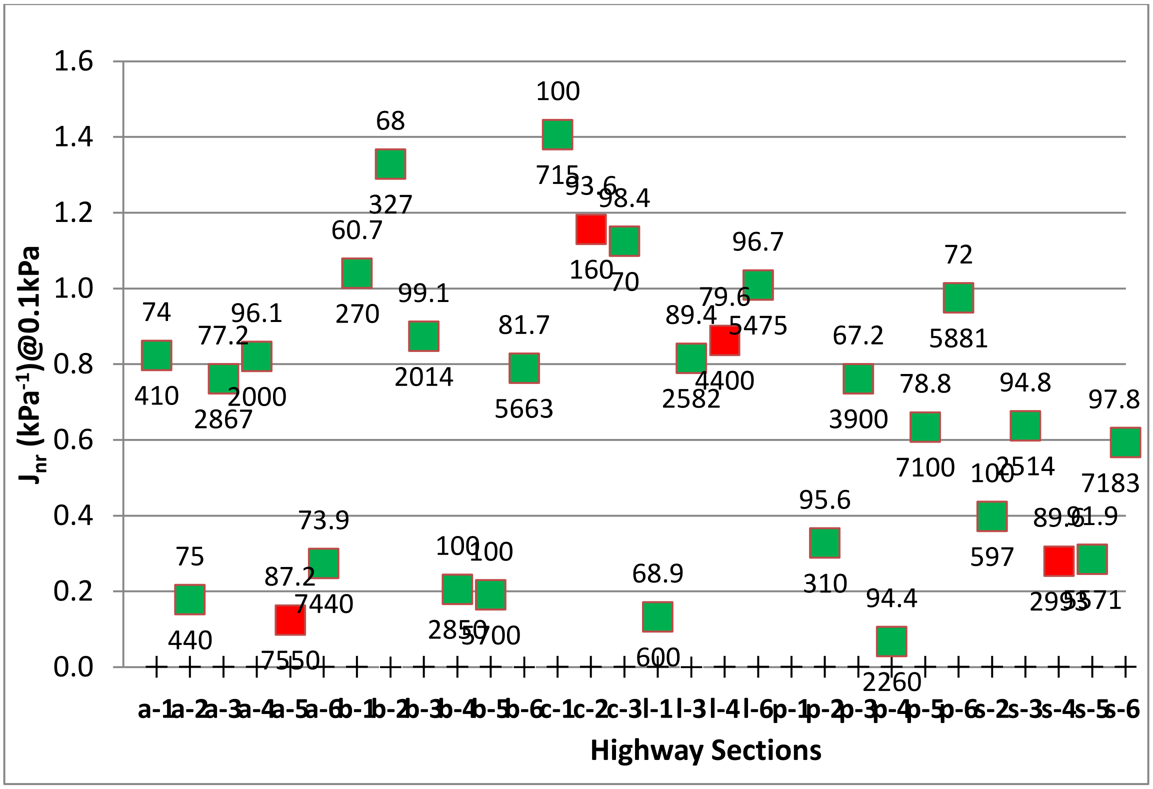


Figure 45: J_{nr} @ 0.1 kPa for all HSs

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

The validation of the SPG system with additional tests was undertaken to develop a reliable performance-based specification for surface treatments. Table 18 shows the modified SPG specification based on the results of this study.

Table 18: Modified SPG Specification

Only three SPG grades are shown, but the grades are unlimited and can be extended in both directions of the temperature spectrum using 3˚C increments for the high temperature and low temperature grades.	Performance Grade											
	SPG 64				SPG 67				SPG 70			
	-13	-16	-19	-22	-13	-16	-19	-22	-13	-16	-19	-22
Average 7-day Maximum Surface Pavement Design Temperature, °C	<64				<67				<70			
Minimum Surface Pavement Design Temperature, °C	>-13	>-16	>-19	>-22	>-13	>-16	>-19	>-22	>-13	>-16	>-19	>-22
Original Binder												
Dynamic Shear, AASHTO T 315/ASTM D7175 *G*/Sin δ*, Minimum: 0.65 kPa Test Temperature @10 rad/s, °C	64				67				70			
Shear Strain Sweep % strain @ $0.8G_i^*$, Minimum: 15 Test Temperature @10 rad/s linear loading from 1-50% strain, 1 sec delay time with measurement of 20-30 increments, °C	25				25				25			
Pressure Aging Vessel (PAV) Residue (AASHTO PP1)												
PAV Aging Temperature, °C	100				100				100			
Creep Stiffness, AASHTO T 313/ASTM D6648 S, Maximum: 500 MPa m-value, Minimum: 0.21 Test Temperature @ 8s, °C	-13	-16	-19	-22	-13	-16	-19	-22	-13	-16	-19	-22
Shear Strain Sweep G_i^*, Maximum: 2.5 MPa Test Temperature @10 rad/s linear loading at 1% strain and 1 sec delay time, °C	25				25				25			

Based on the comparison of the emulsion residue recovery methods evaluated, the Texas oven method (proposed ASTM D7497-09 Method B) is recommended for use with this specification. The laboratory results mostly identified modified binders as superior to unmodified binders. For about 51% (15 of 29) of the HSs, the SPG binder grade predictions based on the laboratory results based on temperature criteria proposed in existing SPG (Table 2) were correlated with field performance. Given the random selection of the pavement sections based on construction schedules and the lack of control over construction practices and design modifications, these results were considered valid and could be used to improve the SPG specification. The large number of laboratory failures at the low temperature limit affected the correlation between the laboratory and field results. This issue was corrected by revising the BBR m-value threshold. Further, many sections that did not meet the recommended strain sweep criteria exhibited adequate field performance. The strain sweep limit was developed using a limited dataset in the existing SPG specification. With the data available from more than 25 sections in this study, the strain sweep limit was revised to better reflect the strain tolerance of surface binders in the field. With these revisions, the correlation between the SPG results and the field performance results increased to approximately 79%.

Closely monitoring the design and construction aspects would allow for the inclusion of additional parameters in the specification. It is suggested that the specification be used in conjunction with other established guidelines and upcoming research findings to construct superior quality pavements. While this study attempted to analyze the behavior of the most common types of surface treatment materials used in Texas, further testing may be required to characterize the properties of other binder types not included in this study. It may also be prudent to conduct additional performance monitoring sessions to confirm whether highway sections with low traffic volumes deteriorate owing to the accumulation of traffic and environmental loads and the aging of the binders. Lastly, in addition to the measurable properties of the binders, design, quality control, and construction techniques contribute to the field performance of surface treatments. Therefore, the application of the SPG specification does not necessarily ensure the adequate performance of surface treatments.

Recommended Future Research

Based on the results of this study, the following is recommended for subsequent studies:

- It is recommended that the HSs included in this study be further monitored for performance issues with the accumulation of traffic and environmental loads.
- Further validation of the SPG specification is recommended with additional sections from Texas and other regions covering a wider variety of materials.
- Further research is recommended on the correlation of the emulsion residue MSCR parameters (J_{nr} and percent recovery) to field performance, particularly in the case of modified binders.

- The possibility of replacing the measured BBR stiffness and m-value with values predicted from the DSR frequency sweep results should be further explored. The equations used for the conversion of the DSR parameters into the BBR parameters should be modified to enable predictions at lower BBR test temperatures and loading times. Further, results that are more accurate may be obtained by using a DSR instrument capable of maintaining test temperatures under 5°C.
- While the Texas oven method produces residue that is similar to that obtained in the field, further evaluation of the recovery method may be required in terms of variability with the material and size of the silicone mat and placement of the samples in the draft oven.

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APPENDIX A

SUMMARY OF SPG TEST RESULTS

Table A1: Laboratory 'Pass'/'Fail' Results

HS ID	Binder Type	Environment		SPG Grade	Fail/Pass[1]
		Zone	Temperature Range (°C)[2]		
a-1	AC 20-5TR	Wet-Cold	67-19	70-13	Fail @ T_L
a-2	AC 20-5TR		67-16	67-16	Pass
a-3	AC 20-5TR		67-16	70-16	Pass
a-4	AC 20-5TR		67-16	73-16	Pass
a-5	AC 20-5TR		67-16	70-16	Pass
a-6	AC 20-5TR		67-19	67-16	Fail @ T_L
b-1	CRS-2	Moderate	70-22	64-10	Fail @ $T_{H\&L}$
b-2	CRS-2		70-19	67-13	Fail @ $T_{H\&L}$
b-3	CRS-2P		70-19	70-10	Fail @ T_L
b-4	AC 20-5TR		67-19	76-16	Fail @ T_L
b-5	AC 20-5TR		67-19	76-16	Fail @ T_L
b-6	AC 20-5TR		70-19	76-16	Fail @ T_L
c-1	AC 10	Dry-Cold	70-22	64-16	Fail @ $T_{H\&L}$
c-2	AC 10		70-22	64-19	Fail @ $T_{H\&L}$
c-3	AC 10		70-25	64-19	Fail @ $T_{H\&L}$
l-1	CRS-2P	Wet-Warm	67-16	76-19	Pass
l-3	AC 20-5TR		67-16	73-16	Pass
l-4	AC 20-5TR		67-19	73-16	Fail @ T_L
l-6	AC 20-5TR		67-16	70-19	Pass
p-1	CRS-2P	Wet-Cold	70-19	76-16	Fail @ T_L
p-2	CRS-2P		67-19	70-16	Fail @ T_L
p-3	AC 20-5TR		67-19	79-16	Fail @ T_L
p-4	AC 20-5TR		67-19	70-19	Pass
p-5	AC 20-5TR		67-19	67-19	Pass
p-6	AC 20-5TR		67-19	70-16	Fail @ T_L
s-2	AC 15P	Dry-Warm	70-13	73-22	Pass
s-3	AC 15P		70-16	73-13	Fail @ T_L
s-4	AC 15P		67-16	70-19	Pass
s-5	AC 15P		67-16	73-19	Pass
s-6	AC 15P		70-13	70-19	Pass

[1] T_H = higher temperature limit, T_L = lower temperature limit, $T_{H\&L}$ = higher and lower temperature limits
[2] Temperature range = obtained from weather station closest to HS

Table A2: DSR and BBR Parameters at Expected Field Temperatures (98% Reliability)

HS ID	Binder	G*/Sin δ @ Environment (T_H)	S @ Environment (T_L)	m @ Environment (T_L)	Pass/ Fail	Pass/Fail by SPG increments
a-1	AC 20-5TR	1.04	326.08	0.21	Fail	Fail
a-2	AC 20-5TR	0.80	101.22	0.26	Pass	Pass
a-3	AC 20-5TR	0.92	247.87	0.27	Pass	Pass
a-4	AC 20-5TR	1.46	159.91	0.30	Pass	Pass
a-5	AC 20-5TR	1.30	239.71	0.26	Pass	Pass
a-6	AC 20-5TR	0.84	482.80	0.22	Fail	Fail
b-1	CRS-2	0.47	562.51	0.20	Fail	Fail
b-2	CRS-2	0.68	582.69	0.21	Fail	Fail
b-3	CRS-2P	0.90	315.96	0.22	Fail	Fail
b-4	CRS-2P	1.26	543.91	0.23	Fail	Fail
b-5	CRS-2P	1.17	486.75	0.23	Fail	Fail
b-6	AC 20-5TR	1.64	378.07	0.25	Pass	Fail
c-1	AC 10	0.47	473.99	0.19	Fail	Fail
c-2	AC 10	0.39	490.06	0.23	Fail	Fail
c-3	AC 10	0.45	601.63	0.23	Fail	Fail
l-1	CRS-2P	1.55	191.97	0.27	Pass	Pass
l-3	AC 20-5TR	1.91	266.04	0.28	Pass	Pass
l-4	AC 20-5TR	1.35	286.46	0.26	Pass	Fail
l-6	AC 20-5TR	0.98	147.71	0.30	Pass	Pass
p-1	CRS-2P	1.51	268.63	0.23	Fail	Fail
p-2	CRS-2P	1.23	272.74	0.24	Pass	Fail
p-3	AC 20-5TR	2.42	335.35	0.24	Fail	Fail
p-4	AC 20-5TR	1.11	282.30	0.25	Pass	Pass
p-5	AC 20-5TR	0.88	305.03	0.24	Pass	Pass
p-6	AC 20-5TR	0.93	320.12	0.23	Fail	Fail
s-2	AC 15P	1.66	30.52	0.31	Pass	Pass
s-3	AC 15P	1.09	66.66	0.26	Pass	Fail
s-4	AC 15P	1.18	62.77	0.28	Pass	Pass
s-5	AC 15P	0.96	342.89	0.25	Pass	Pass
s-6	AC 15P	1.27	60.83	0.33	Pass	Pass

Table A3: Strain Sweep Results

HS ID	Binder	Strain Sweep (%γ at 0.80Gi*)	Aged Gi* (MPa, at 1% γ)
A-1	AC 20-5TR	31.28	0.57
A-2	AC 20-5TR	25.85	0.61
A-3	AC 20-5TR	30.23	0.57
A-4	AC 20-5TR	27.39	0.29
A-5	AC 20-5TR	29.11	0.69
A-6	AC 20-5TR	25.1	1.17
B-1	CRS-2	13.53	1.58
B-2	CRS-2	Invalid	1.53
B-3	CRS-2P	16.49	0.82
B-4	CRS-2P	35.69	1.54
B-5	AC 20-5TR	31.85	1.26
B-6	AC 20-5TR	Invalid	1.13
C-1	AC 10	15.22	1.21
C-2	AC 10	11.6	1.64
C-3	AC 10	15.01	1.27
L-1	CRS-2P	13.32	1.20
L-3	AC 20-5TR	Invalid	0.71
L-4	AC 20-5TR	24.63	1.02
L-6	AC 20-5TR	33.19	0.69
P-1	CRS-2P	13.4	0.63
P-2	CRS-2P	14.89	0.90
P-3	AC 20-5TR	26.21	0.78
P-4	AC 20-5TR	18.75	0.77
P-5	AC 20-5TR	17.43	0.77
P-6	AC 20-5TR	20.71	1.01
S-2	AC 15P	18.92	0.57
S-3	AC 15P	16.17	0.35
S-4	AC 15P	27.04	0.37
S-5	AC 15P	25.19	0.59
S-6	AC 15P	18.87	0.53

Table A4: MSCR Test Results

HS ID	Binder Type	J_{nr} (kPa^{-1}) @0.1kPa	Percent Recovery (%) @0.1kPa	J_{nr} (kPa-1) @3.2kPa	Percent Recovery (%) @3.2kPa
A-1	AC 20-5TR	0.823	30.293	1.272	3.416
A-2	AC 20-5TR	0.178	55.717	0.303	23.051
A-3	AC 20-5TR	0.761	36.856	1.302	4.939
A-4	AC 20-5TR	0.820	27.625	1.313	4.157
A-5	AC 20-5TR	0.124	73.947	0.480	9.880
A-6	AC 20-5TR	0.273	54.653	0.557	15.832
B-1	CRS-2	1.040	5.978	1.271	-0.216
B-2	CRS-2	1.328	8.367	1.594	-0.410
B-3	CRS-2P	0.873	33.165	1.824	-0.105
B-4	AC20-5TR	0.205	111.449	2.773	0.551
B-5	AC 20-5TR	0.294	105.539	2.866	0.313
B-6	AC 20-5TR	0.789	35.466	1.567	2.697
C-1	AC 10	1.406	1.743	1.531	-0.578
C-2	AC 10	1.156	3.299	1.258	-0.346
C-3	AC 10	1.124	4.755	1.241	-0.323
L-1	CRS-2P	0.132	101.465	0.568	51.416
L-3	AC 20-5TR	0.815	26.459	1.311	3.071
L-4	AC 20-5TR	0.863	23.786	1.376	2.599
L-6	AC 20-5TR	1.009	14.053	1.394	1.260
P-1	CRS-2P	0.531	84.935	1.950	7.433
P-2	CRS-2P	0.327	74.804	0.869	27.524
P-3	AC 20-5TR	0.761	26.548	1.339	2.089
P-4	AC 20-5TR	0.067	111.274	1.453	6.639
P-5	AC 20-5TR	0.634	38.575	1.266	3.970
P-6	AC 20-5TR	0.975	22.664	1.533	1.649
S-2	AC 15P	0.398	62.548	1.122	6.809
S-3	AC 15P	0.637	23.359	1.088	2.512
S-4	AC 15P	0.280	63.862	0.599	21.587
S-5	AC 15P	0.284	62.781	0.599	21.197
S-6	AC 15P	0.592	24.247	0.869	5.737

Table A5: Frequency Sweep Predictions of BBR Parameters

HS ID	Expected T_L @ 98% Reliability (°C)	Predicted S (MPa) @ Expected T_L	Predicted m-value @ Expected T_L	SPG T_L(°C)	Fail/Pass
A-1	-17.68	259.9629	0.229905	-16	Fail
A-2	-15.174	327.5641	0.289463	-16	Pass
A-3	-15.174	152.9353	0.332945	-25	Pass
A-4	-13.644	157.3181	0.331262	-19	Pass
A-5	-15.88	302.4073	0.267361	-16	Pass
A-6	-17.68	259.1588	0.224638	-16	Fail
B-1	-20.304	361.7172	0.203773	-13	Fail
B-2	-17.886	445.3761	0.132598	-7	Fail
B-3	-17.886	363.6347	0.320169	-19	Pass
B-4	-18.204	1853.408	0.199883	-7	Fail
B-5	-18.204	498.48	0.128373	-10	Fail
B-6	-17.886	448.7305	0.225053	-13	Fail
C-1	-20.268	439.8662	0.176287	-10	Fail
C-2	-21.528	587.8432	0.194527	-13	Fail
C-3	-23.692	606.375	0.16439	-10	Fail
L-1	-15.774	258.214	0.28844	-19	Pass
L-3	-15.774	293.6515	0.245101	-13	Pass
L-4	-16.098	414.0563	0.273942	-16	Pass
L-6	-14.692	244.2622	0.288802	-16	Pass
P-1	-18.18	365.5287	0.247788	-16	Pass
P-2	-18.074	450.4734	0.286229	-16	Pass
P-3	-18.174	307.4045	0.307419	-22	Pass
P-4	-18.692	346.9023	0.285679	-22	Pass
P-5	-18.18	388.0174	0.263874	-19	Pass
P-6	-18.174	Invalid	Invalid	Invalid	Fail
S-2	-11.52	75.96238	0.282647	-13	Pass
S-3	-13.668	80.66664	0.318977	-34	Pass
S-4	-13.88	99.35555	0.324828	-28	Pass
S-5	-13.88	102.1206	0.316903	-28	Pass
S-6	-12.538	94.05923	0.332239	-19	Pass

Table A6: FT-IR Results (Carbonyl Areas)

Section	Recovery Method	Binder Type	Carbonyl Area			Average Carbonyl Area
			Test 1	Test 2	Test 3	
P-2	Method A	CRS-2P	0.621	0.67	0.654	0.648
	Method B	CRS-2P	0.613	0.605	0.628	0.615
P-1	Method A	CRS-2P	0.585	0.599	0.607	0.597
	Method B	CRS-2P	0.573	0.552	0.614	0.580
B-2	Method A	CRS-2	0.749	0.729	0.743	0.740
	Method B	CRS-2	0.659	0.664	0.641	0.655
B-3	Method A	CRS-2P	0.617	0.563	0.57	0.589
	Method B	CRS-2P	0.564	0.61	0.594	0.589
B-1	Method A	CRS-2	0.619	0.593	0.61	0.607
	Method B	CRS-2	0.6	0.589	0.581	0.590
L-1	Method A	CRS-2P	0.663	0.66	0.667	0.662
	Method B	CRS-2P	0.597	0.589	0.583	0.593

APPENDIX B

SPG AND FIELD PERFORMANCE RESULTS

HS ID	SPG Specification[3]	Field Performance[4]	SCI_{AL}	SCI_{BL}	$SCI_{OVERALL}$	Match[5]
A-1	Fail	Pass	70.5	88	74	No
A-2	Pass	Pass	72.5	85	75	Yes
A-3	Pass	Pass	71.5	100	77.2	Yes
A-4	Pass	Pass	100	80.5	96.1	Yes
A-5	Pass	Pass	100	36	87.2	Yes
A-6	Fail	Pass	67.5	99.5	73.9	No
B-1	Fail	Fail	51	99.5	60.7	Yes
B-2	Fail	Fail	60	100	68	Yes
B-3	Fail	Pass	99	99.5	99.1	No
B-4	Fail	Pass	100	100	100	No
B-5	Fail	Pass	100	100	100	No
B-6	Fail	Pass	81.5	82.5	81.7	No
C-1	Fail	Pass	100	100	100	No
C-2	Fail	Pass	100	68	93.6	No
C-3	Fail	Pass	100	92	98.4	No
L-1	Pass	Fail	62.5	94.5	68.9	No
L-3	Pass	Pass	87	99	89.4	Yes
L-4	Fail	Pass	83.5	64	79.6	No
L-6	Pass	Pass	100	83.5	96.7	Yes
P-2	Fail	Pass	94.5	100	95.6	No
P-3	Fail	Fail	59	100	67.2	Yes
P-4	Pass	Pass	99	76	94.4	Yes
P-5	Pass	Pass	73.5	100	78.8	Yes
P-6	Fail	Pass	65	100	72	No
S-2	Pass	Pass	100	100	100	Yes
S-3	Fail	Pass	99.5	76	94.8	No
S-4	Pass	Pass	93	76	89.6	Yes
S-5	Pass	Pass	99	63.5	91.9	Yes
S-6	Pass	Pass	100	89	97.8	Yes

[3] Pass = Binder met environmental temperature demand @ 98% reliability in the given location in terms of the SPG threshold values
Fail = Binder failed to meet environmental temperature demand @ 98% reliability in the given location in terms of the SPG threshold values
[4]Pass = Adequate performance of HS with overall SCI score ≥ 70%
Fail = Inadequate performance of HS with overall SCI score < 70%
[5]Yes = Good correlation between the SPG specification and field performance
No = No correlation between the SPG specification and field performance

VITA

Name: Aishwarya Vijaykumar

Address: 501G CE/TTI, 3136 TAMU, Zachry Department of Civil Engineering
College Station, TX 77843-3136

Email Address: aish.vijay.k@gmail.com

Education: B.Tech., Civil Engineering, Jawaharlal Nehru Technological University, 2006

Research Interests: Testing and Characterization of Bituminous Materials; Asphalt Rheology